PRECISION LOCATION OF UNDERGROUND NUCLEAR EXPLOSIONS USING TELESEISMIC NETWORKS AND PREDETERMINED TRAVEL-TIME ANOMALIES

1 March 1968

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C.

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Under

Project VELA UNIFORM

Sponsored By

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
ARPA Order No. 624

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PRECISION LOCATION OF UNDERGROUND NUCLEAR EXPLOSIONS USING TELESEISMIC NETWORKS AND PREDETERMINED TRAVEL-TIME ANOMALIES

SEISMIC DATA LABORATORY REPORT NO. 214

AFTAC Project No.:	VELA T/6702
Project Title:	Seismic Data Laboratory
ARPA Order No.:	624
ARPA Program Code No.:	5810
Name of Contractor:	TELEDYNE, INC.
Contract No.:	F 33657-67-C-1313
Date of Contract:	2 March 1967
Amount of Contract:	$ 1,736,617
Contract Expiration Date:	1 March 1968
Project Manager:	William C. Dean (703) 836-7644

P. O. Box 334, Alexandria, Virginia

<u>AVAILABILITY</u>

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Wash, D.C. 20333

This research was supported by the Advanced Research Projects Agency, Nuclear Test Detection Office, under Project VELA-UNIFORM and accomplished under the technical direction of the Air Force Technical Applications Center under Contract F 33657-67-C-1313.

ABSTRACT

Using a series of 19 explosions with accurately known epicenters within a 2500 km^2 area of the Nevada Test Site, the location effectiveness is demonstrated of applying predetermined travel-time anomalies to a limited network of teleseismic stations (comprised of between 4 and 13 stations greater than 1900 km distance). Three different travel-time tables were used: Jeffreys-Bullen; Herrin 1961 version; and Herrin, November 1966 version; and two different computer programs: LOCATE and SHIFT, the former which minimizes the sum of squares of residuals and the latter which minimizes the sum of squares of relative residuals. The mean location error for the 19 known epicenters, obtained without time anomalies, is about 26 km, and with anomalies is less than 3 km, regardless of travel-time table and regardless of program.

It is further demonstrated that neither the number of stations in the range of 3 or 4 to 13 nor the distance aperture of the network has an effect on the location of known surface events, although the azimuth aperture does.

Confidence estimates are made in three ways: the standard confidence ellipses; maximum-relative-error polygons; and standard-deviation contours about the final solution. It is shown that by applying travel-time anomalies, the standard confidence ellipses, which estimate the reliability of the data in a least squares sense, can be reduced in area by factors of 1/5 to 1/152 and still enclose the true epicenter.

A discussion is given of the stability of travel-time anomalies across the Nevada Test Site area, and of some problems involved in determining usable anomalies from earthquakes.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Mr. R. O. Ahner for his assistance in seismic analysis and in program writing and modification; to Mrs. H. N. Johnson for her assistance in data reduction and to the research staff of the Seismic Data Laboratory with whom many fruitful discussions were held.

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INTRODUCTION

It has been well-established that station time residuals and travel-time anomalies (relative residuals) are not constant but change significantly from one epicentral region to another at a rate dependent upon the region and the station or, with travel-time anomalies, upon the station-pair separation (see, for example, Chiburis and Dean, 1965; Chiburis, 1966a,b, and 1968). However, the time errors are reasonably well-behaved within each region such that they can be predicted (time-calibrated) for additional events occurring in the same region.

Any location scheme which assumes that there are no time errors other than those due to reading; or that a regional or azimuthal correction is valid for all stations in a network; or that a single-station correction for one region is adequate for another will necessarily do a poor job of locating epicenters. This report then, is primarily concerned with the teleseismic location accuracy obtainable for a particular region by using either station residuals, travel-time anomalies, or no corrections at all. Secondarily, we are concerned with the performance of two computer programs presently in use at the Seismic Data Laboratory, LOCATE and SHIFT. The principal difference between the two programs is that SHIFT minimizes in a least-squares sense the relative-anomaly errors rather than the absolute residuals.

Also investigated is a technique whereby limits of the solution are estimated either on the basis of an acceptable network standard deviation of time errors or of maximum relative-time errors at any station pair within the network.

DEFINITIONS

Travel-Time Anomaly.

The travel-time anomaly at station i relative to station j is defined as

$$A_{i/j} = T_i - T_j - H_i + H_j + e_i - e_j$$

where T is the observed arrival time, H is the expected travel time according to some travel-time and distance relationship, and e is a correction for ellipticity. In this report, values of H were computed from the Jeffreys-Bullen, Herrin 1961, and Herrin 1966 (November) travel-time tables. The above definition of anomaly makes no assumptions concerning crustal P-wave velocities (for station elevation corrections); it simply measures the net effect of all causes of travel-time errors at any station with respect to any arbitrary reference station.

Residuals.

The residual at station i is

$$R_i = T_i - T_o - (H_i + d_i)$$

where T_o is event origin time and d_i is a correction both for ellipticity and for the elevation of the ith station assuming a value for the angle of incidence and for the P-wave velocity between the station and sea-level. Here, H is computed from the Herrin 1961 table which is the standard relationship in the particular version of LOCATE used for this report.

METHOD

The program LOCATE uses the standard Geiger technique, briefly described as follows:

Let the errors which are to be minimized in a least-squares sense be defined as

$$E_i = R_i^! - R_i^o + R_i$$

where R_i^o is the observed residual at station i, R_i is the previously-determined residual for that region and $R_i^!$ is a theoretical residual such that

$$R_i^! \equiv f(\lambda, \phi, Z, T_o) = \frac{\partial H_i}{\partial \lambda} d\lambda + \frac{\partial H_i}{\partial \phi} d\phi + \frac{\partial H_i}{\partial Z} dZ + \frac{\partial H_i}{\partial T_o} dT_o$$

where λ, ϕ, Z, and T_o are respectively the event longitude, latitude, depth, and origin time, and H is the expected travel time. As a change in origin time is the same as a change in expected travel time,

$$\frac{\partial H_i}{\partial T_o} \equiv 1.$$

Also, to compare the two programs more closely, depths were restrained throughout such that

$$\frac{\partial H_i}{\partial Z} \equiv 0.$$

Therefore

$$R_i^! = \frac{\partial H_i}{\partial \lambda} d\lambda + \frac{\partial H_i}{\partial \phi} d\phi + dT_o$$

It is desired that $\sum_{i=1}^{N} E_i^2$ be a minimum for N stations so

$$\frac{\partial}{\partial \mu_k} \left(\sum_{i=1}^{N} E_i^2 \right) \equiv 0 \qquad k = 1,2,3$$

where $\mu_1 = d\lambda$, $\mu_2 = d\phi$, and $\mu_3 = dT_o$.

This differentiation yields three normal equations which can be solved simultaneously for the errors in the event parameters $d\lambda$, $d\phi$, and dT_o.

The program SHIFT, on the other hand, defines an anomaly error at station i relative to station j as

$$dA_{i/j} = A_{i/j} - \bar{A}_{i/j}$$

where $\bar{A}_{i/j}$ is the previously-determined relative anomaly for that region. The relative errors to be minimized in a least-squares sense are

$$E_{i/j} = dA'_{i/j} - dA_{i/j}$$

where $dA'_{i/j}$ are the theoretical relative anomalies such that

$$dA'_{i/j} \doteq \frac{\partial A_{i/j}}{\partial \lambda} d\lambda + \frac{\partial A_{i/j}}{\partial \phi} d\phi + c_j$$

where c_j is the average error, or bias, at the reference station j. It is desired to minimize $\sum_{i=1}^{N} E_{i/j}^2$, so, as before,

$$\frac{\partial}{\partial \mu_k} \left(\sum_{i=1}^{N} E_{i/j}^2 \right) \doteq 0 \qquad k = 1,2,3$$

where $\mu_1 = d\lambda$, $\mu_2 = d\phi$, and $\mu_3 = c_j$. Solving these three normal equations yields the event-parameter corrections $d\lambda$, $d\phi$, and the reference-station bias c_j.

DESCRIPTION OF THE DATA

All of the time data used in this study were derived from nuclear explosions detonated within the Nevada Test Site (NTS) area (Figure 1). Table I lists the event information. The events selected as references from which residuals and anomalies were measured are Bilby or Tan, the series of Bronze, Corduroy, and Buff, or the series of Nash, Agile, and Commodore. These several events were necessary so that residuals or anomalies could be obtained for an adequate number of recording stations. Table II lists the station anomalies, relative to RK-ON, computed from the three travel-time tables, in addition to the residuals computed from the Herrin/1961 table. A key letter, indicating which series of events were used as references in determining the corrections, is given in the last column.

PROCEDURE

Station records of all explosions were routinely read, with the identical networks of stations and arrival times being used for both programs. Depths for all events were restrained to the surface. Raw arrival times (Table III) were input to SHIFT and used within the program in conjunction with the appropriate input travel-time anomalies. For LOCATE, station arrival times were corrected by the residuals prior to their input into the program. These input times for LOCATE are obtained by subtracting the residuals in Table II from the arrival times input to SHIFT (Table III).

A description on the use of program SHIFT is given in Appendix I.

RESULTS OF LOCATION

Without Time Corrections.

Table IV lists the location errors, in kilometers, when neither residuals nor anomalies are applied to the event arrival times (the times have been corrected, however, for station elevation and ellipticity). The mean error for 17 events using LOCATE is seen to be 25.8 km and using SHIFT (Herrin 61) 25.9 km; the results from the two programs using the same travel-time table are essentially in agreement. With the J-B and Herrin 66 tables, the results using SHIFT are 27.7 km and 20.8 km respectively. It is not known at this time if the apparently better results obtained by using the Herrin 66 table are significant or not. It would be necessary to locate a larger sample of events to determine the effectiveness of this table for the networks used in this study and for the NTS area.

The resultant average errors of about 26 km demonstrate the best one could hope to do when no allowances are made for residuals (LOCATE) or anomalies (SHIFT).

With Time Corrections.

When the residuals or anomalies are determined for a particular region, such as the Nevada Test Site, and for each station which is to be used in subsequent location networks, the resultant location errors can be reduced by at least an order of magnitude. Table V lists the location errors, in kilometers, when either residuals (LOCATE) or relative anomalies (SHIFT) are applied to the event arrival times. The mean error for 17 events using LOCATE is now seen to be 2.98 km and using SHIFT (Herrin 61) 2.86 km. Again, the mean values from either program are in agreement, although individual event locations differ by as much as 4.1 km between the two methods. This difference implies, of course, that the programs are computing in significantly different ways but yield about the

same answer on the average. Using the J-B and Herrin 66 tables, the SHIFT mean errors are 2.92 km and 2.59 km respectively which suggests that when anomalies are applied, any reasonable travel-time table is adequate.

Actual Time Errors.

Although the events used for locating in this study were of a reasonable size which made film reading straightforward, time errors at the stations due to misreading, imperfectly-known anomalies, etc., were far from negligible. Actual time errors at station i relative to mean zero for the jth event are shown in Table VI, computed as

$$E^j_{i/o} = A^j_{i/r} - \bar{A}_{i/r} - \bar{E}^j$$

where A^j is the anomaly for the jth event, $\bar{A}$ is the previously-measured input anomaly for the region of the jth event, and $\bar{E}^j$ is the mean error for the jth event. Also included in this table are the errors for $\bar{A} = 0$ (which assumes that there are no anomalies). Event standard deviations are given at the far right of the table. As shown in the table, the actual standard deviations when anomalies are not used average about 0.86 sec, with errors as high as 1.9 sec. When allowances are made for the anomalies, the actual standard deviations average about 0.16 sec, a reasonable figure for reading error alone, although individual errors are as high as 0.8 sec. The point to be made is that the set of events used for testing the validity of applying anomalies is not unusual, because reading or other time errors are not particularly small, some even being quite large.

A similar study is presently being undertaken in which the set is composed of low-yield events, at least in a signal-to-noise ratio sense. However, selecting this set so that the events are recorded at a significantly smaller size than those used in this study is difficult because several of the events listed in Table I have quite low recorded signal amplitudes due to

deliberately-reduced station magnifications. The computed magnitudes, where known, are given in the following list for all 17 events:

Event	Magnitude
Fore	5.2
Buff	5.1
Chartreuse	5.2
Auk	4.9
Piledriver	5.5
Bourbon	5.1
Dumont	5.5
Agile	Not Calculated
Nash	5.2
Commodore	5.7
Greeley	6.3
Klickitat	5.0
Turf	4.9
Piranha	Not Calculated
Scotch	5.5
Corduroy	5.6
Bronze	5.2

Film Reading of First Extrema.

One of the methods used in this study, which can substantially reduce errors, is to permit readings of times other than those for first motion. Regardless of event size, first motion is usually difficult to read consistently to within 0.1 sec. However, by reading the arrival time of the first extremum (peak) rather than first motion at all stations, timing is considerably more precise. Therefore, most of the events in this study were read for this phase, although a few were so large the traces went off scale forcing the reading of first motion. The excellent location results show that, by reading either

first extrema or first motions, one does not lose, and may actually gain, network capability.

Number of Stations.

The number of stations of which the networks were comprised for locating the set of 17 NTS events varied between 4 and 13. Figure 2 shows the location errors, in kilometers, as a function of the number of stations for SHIFT-H61, both with and without anomalies. The results without anomalies show no dependence on the number of stations, and those with anomalies are too few to derive a clear relation. This result suggests that it is not necessary to require a large number of stations for locating accurately if proper allowances are made for the station travel-time anomalies.

Effect of Aperture.

Figure 3 shows the location errors in kilometers, of the 17 events as a function of azimuth aperture which is calculated as

$$d\theta_i = |\theta_{max} - \theta_{min}|$$

where θ is epicenter-to-station azimuth. Included on the figure are the results obtained both with and without travel-time anomalies. The errors appear to have a fairly certain dependence on the aperture of the azimuth, especially for the results obtained with anomalies. The actual dependence is hard to ascertain due to lack of data points at apertures less than 80°. This effect is presently being investigated.

The effect of distance aperture on the location error is negligible, as seen in Figure 4, both with and without anomalies.

CONFIDENCE REGIONS

Confidence regions were computed within SHIFT in the usual manner (e.g., Flinn, 1965) for all events, both with and without travel-time anomalies. Table VII lists, by event, the areas of the computed ellipses and the factors of reduction in ellipse areas when anomalies are used. Without anomalies, two events (Fore and Chartreuse) were not within the ellipse at the 95% level. With anomalies, all events were within the ellipse and the ellipses were reduced in area by factors of 5 to 152, with an average reduction of about 45. This reduction in ellipse area points out the necessity and value of travel-time anomalies.

Maximum Relative Errors.

When computations are made for confidence regions, the variances, or standard deviations, of the final solutions are used in the estimates. These variances are merely indicators of the goodness-of-fit in the least-squares procedures and if the number of degrees of freedom is small, the variances and, hence, the confidence-region estimates become unrealistic. (In fact, when as few as three stations are used, no estimate at all can be made of the location error, as the solution is unique). For example, the events Bourbon and Scotch have respectively actual standard deviations of 0.08 and 0.23 sec (Table VI, with travel-time anomalies) and N=4 and 5. The ellipse area for Bourbon is 7118 km^2 and the location error is 1.9 km, while for Scotch the area is 2309 km^2 and the error is 5.0 km. Both ellipse areas are abnormally high due strictly to the small number of stations used in locating, although the time data from these stations and the network apertures are as good as the data and apertures from the other networks. Therefore, when few stations are used in locating events, it may be of value to estimate the location error by considering the maximum permissable relative time error at any station-pair in the network rather than a statistical estimate using the variance of the

goodness-of-fit. In this way fairly good estimates of location error can be made even when the number of stations is three.

Figure 5 shows the maximum relative errors (X100) using Bourbon data for a grid of locations about the final SHIFT solution. This grid is computed as an option within SHIFT by subroutine SIGRID. The scale in latitude is 1.0 km and in longitude 2.4 km between center points of each number field of 4 spaces. With this proportion, the scale is equal in all directions. The errors at each grid point are computed as

$$E_{i/r} = T_i - H_i - T_r + H_r - \overline{A}_{i/r} \qquad i = 1,2,\ldots,N$$

where all quantities have previously been defined. The maximum relative error, regardless of reference station bias, from this set of N errors is then

$$E_{max} = (E_{i/r})_{max} - (E_{i/r})_{min}$$

at each grid point.

The dashed-line polygon in Figure 5 is the contour of the (known) maximum relative error (0.18 sec) at the true epicenter marked at X. The circle enclosing the value 0.11 is the maximum relative error as a result of the final solution obtained with SHIFT-H61. The solid-line polygon is the contour of the maximum relative error estimated to be 0.4 sec (0.3 sec higher than that at the final solution) for this event. A seismic analyst can usually estimate his reading errors quite well, and if the effects of previously-determined relative travel-time anomalies are removed (they must be determined, not estimated), the estimates can be used to contour the maximum relative error. A relative error estimate of 0.4 sec is liberal for an event of the size of Bourbon, but it is an example of the manner of using any estimate. The approximate area of the estimated polygon is less than 340 km^2. The area of the corresponding ellipse previously computed (Table VII) is 7118 km^2.

Figure 6 shows similar results for Scotch. Again, an error estimate 0.3 sec higher than that obtained from the final solution (0.5 sec) is used to contour 0.8 sec. The approximate area of the estimated polygon is less than 400 km^2 compared to 2309 km^2 of the standard confidence ellipse.

Although Scotch was a large event and the reading errors were expected to be small, an actual maximum relative error of 0.7 sec is observed. The reason for this appears to be the slight instability of the relative anomalies for the Nevada Test Site. Scotch was located about 40 km to the northwest of Bourbon, and hence about 40 km from the area of the reference events used for determining the anomalies. For networks the size of that used for Scotch (80° azimuth aperture), it is not surprising that the anomalies are not constant.

Figures 7 and 8 show the maximum-relative-error grid for a network of three stations obtained by deleting SV3QB from Bourbon and SV3QB and PG-BC from Scotch. For three stations, it is impossible to estimate the location errors by the usual means as the statistical degrees of freedom are reduced by zero. However, with maximum relative errors, reliable estimates can be made. Again, for Bourbon, which is located within the area of the reference events, an error estimate of 0.4 sec is contoured (Figure 7), and for Scotch, 40 km from the area of the reference events, an error estimate of 0.7 sec is used (Figure 8). The approximate areas of the polygons for Bourbon and Scotch are 350 km^2 and 630 km^2 respectively. Therefore, by using estimates of the maximum relative errors, reasonable estimates of location errors can be made when the usual statistical confidence estimates are impossible to compute.

Standard Deviation Ellipses.

Subroutine SIGRID also produces an output of network standard deviations, in addition to the maximum relative errors, for a similar set of grid positions.

Figure 9 shows the zero-mean standard deviation output for Bourbon, with anomalies. The values (X100) at each grid point k are computed as

$$\sigma_k = \left[\frac{\sum_{i=1}^{N} (A^k_{k/r} - \bar{A}_{i/r} - E_r)^2}{N-2} \right]^{1/2}$$

where A^k is the computed anomaly at k, $\bar{A}$ is the predetermined anomaly, and E_r is the average error, or bias, at the reference station r. This output actually shows how the least-squares procedure within SHIFT minimizes the sum of squares (or standard deviation) of errors. Tne dashed-line ellipse is the contour of the known standard deviation of time errors for Bourbon. The standard confidence ellipse would be the same as that shown in Figure 5.

Therefore, by using the parameters of the computed confidence ellipse, the maximum-relative-error SIGRID, and the standard-deviation SIGRID, the utmost information is being elicited from the time data.

IMPROVING THE ESTIMATES OF TRAVEL-TIME ANOMALIES

The computed travel-time anomalies used in this report were derived from a few selected reference events to show the teleseismic network capability for locating events in the Nevada Test Site area. It is known that the anomalies, for some stations and for this area, are not constant but exhibit some variability at different positions within the area shown in Figure 1. A much better estimate of the true travel-time anomaly for the NTS area can be obtained by averaging the anomalies at each station for all 19 events in this study. These average anomalies, given in Table VIII using the Herrin 66 travel-time table, should be used for locating new events in the NTS area when a network is comprised of any of the listed stations. Table VIII is a computer output of program TIMEANOM; the key circled numbers shown are described in Appendix II. Tables IX and X list the station anomalies for the Jeffreys-Bullen and Herrin 61 travel-time tables respectively.

Other Variables for Computing Anomalies.

All of the station anomalies in this report were, of course, computed from nuclear explosions, the positions of which are extremely well known in the three dimensions of latitude, longitude, and depth. Past studies (Chiburis and Dean, ibid, and Chiburis, ibid) and studies currently in progress show that earthquakes are not quite so well behaved as explosions for several reasons. First, simple epicenter mislocations can yield errors in anomaly estimates as high as two or three seconds for large networks. The mislocation effect is described in Chiburis and Dean, ibid, p. 31 ff. Second, and perhaps more serious, depth effects must be taken into account. There are no reasons to suppose that the anomalies measured for shallow events in a particular region may not change significantly for deep events in the same region. Added to these effects are the problems of depth errors in the located events.

One of the current studies at the SDL has shown conclusively that for a North American Network of 21 LRSM stations, the station anomalies computed from the explosion LONG SHOT on Amchitka Island are not in as good agreement as expected with the anomalies computed from earthquakes in the large region of the Rat-Andreanof Is. at depths of 15 km to 300 km (discrepancies as large as 1.5-2.0 sec). At least part of the difficulty seems to be associated with hypocenter mislocation, because when the set of earthquakes was relocated by using the LONG SHOT anomalies, most of the epicenters shifted an average of about 50 km after which, in general, the serious time errors were significantly reduced. Certainly the LONG SHOT anomalies are not valid for all of the events in the set because the linear size of the region is about 800 km or more, much too large for a single set of anomalies to exist throughout, but they should be valid for events very near LONG SHOT and these still shift 40-50 km. Figure 10 shows the directions of the shifts, indicating that large bias effects may exist for the Andreanof locations as reported by the U.S.C. and G.S. This study is continuing.

Anomalies vs. Residuals.

The preceding results indicate that comparable location accuracies for explosions are obtained when using either relative anomalies or absolute residuals. The question may arise then as to what differences, if any, one may expect when trying to determine a true, physical time correction for an earthquake region. Some of the possible differences are as follows:

1. Origin time errors (serious for some earthquakes) play no role when relative times are used; time bias is removed, so that events in the same region may be compared with one another in determining the actual anomaly.

2. First extrema as well as first motions can be read to determine consistent corrections from different events in the same regions. This is important if one has only a few small

events for time calibrating.

3. When using residuals, the defined regions can be greater in number and smaller in area than when using anomalies, and the problem of time calibrating the earth becomes more difficult. A simple case qualitatively illustrates this point where Figure 11 shows a geologically faulted area composed of two different crustal media I and II with average P-wave velocities of V_1 and V_2. The network stations are labeled 1, 2, and 3 each having a residual from an event in medium I computes as R_1^I, R_2^I, and R_3^I and anomalies relative to station 1 computed as 0, $A_{2/1}^I$, $A_{3/1}^I$. For an event occurring in region II, however, each of the residuals will have a bias added to them due to the different velocity in the vicinity of the source in this region; the anomalies, however, would be expected to change only slightly because the hypocenter-station raypath differences between the two (teleseismic) sources would be negligible. Hence, for each of the stations there would have to be two residual regions but only one anomaly region. Of course, for stations situated on the side of region II and opposite to the reference station, there would then be two regions for both residuals and anomalies. However, at least some reduction in the time-calibration regionalization should be realized when relative anomalies are used.

CONCLUSIONS

The following conclusions are made concerning the results obtained by analyzing 19 nuclear explosions detonated within a 2500 km^2 area of the Nevada Test Site. Seismograms were used from teleseismic stations forming networks of four to thirteen stations.

1. For limited-station teleseismic networks, the location capability, for 17 events occurring in the Nevada Test Site and without applying previously-determined residuals or travel-time anomalies, is about 26 km, regardless of the program used (LOCATE or SHIFT) and regardless of the travel-time table employed (Herrin 61, Herrin 66, or JB tables).

2. The location capability for the same networks and time data is better than 3 km when previously-determined residuals or travel-time anomalies are applied, regardless of program and travel-time table. That is to say, when these travel-time curves can equivalently be replaced by observed travel times from each station to an accurately known explosion point, the particular curve selected as a standard is essentially irrelevant and epicenters of other nearby explosions can be located within the indicated error limit.

3. The effect of the number of stations in the range from 3 or 4 to 13 on the location capability of the networks used in the study is negligible, either with or without travel-time anomalies.

4. The effect of the range of epicentral distances (distance aperture) on the capability of locating known surface events with the same networks is negligible, either with or without travel-time anomalies.

5. The azimuth aperture has an observable effect on the location capability of the networks where, for apertures down to 60°, the location errors without travel-time anomalies are as high as 60 km, and with anomalies 6 km.

6. The areas of computed confidence ellipses can be reduced by factors of 1/5 to 1/152 with the application of travel-time anomalies and still enclose the event locations which, for this study, are accurately known, as are the explosions used to calibrate the praticular epicenter-station paths used in the study. In effect, these reduced ellipses represent uncertainties in the position of the epicenters relative to the positions of the calibration events.

7. With as few as 4 or 5 stations, computed confidence ellipses with anomalies are unrealistically large due to the small number of statistical degrees of freedom. (The Bourbon explosion, with 4 stations, has an ellipse 7,000 km^2 and a location error of 1.9 km). Estimates of the maximum relative time errors for a network of stations permits more realistic confidence limits to be set on the solution. In this way, Bourbon's confidence polygon is about 340 km^2. Also, as few as three stations can be used to obtain the confidence limits when maximum relative errors are estimated.

8. Travel-time anomalies, computed from a few selected events, show some variability across the NTS area in Figure 1, but the effect on relative location accuracy is small. The size of the area in Figure 1 is about 2500 km^2, implying that fairly large regions are involved for determining reasonably constant anomalies, so the problem of time calibrating a stationary network for any region of the earth from which either explosions at accurately known locations or earthquakes (bias effects not included) are recorded is not formidable. In either case, if accurate locations are not independently known, the epicentral solutions with anomalies included reduce to locations relative to one another with the actual error of the whole set remaining unknown.

9. Relative anomalies for earthquake regions can be simpler to assess than absolute residuals because (a) origin time errors are eliminated; (b) first-extremum anomalies and first motion anomalies from several events can be combined (except when obvious period differences are noted); and (c) depending on the region and on the network geometry, the regions for which the calibrations need to be determined can be fewer in number and larger in area.

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TABLE I

Event Information

Event	Date	Origin Time	Latitude	Longitude	No. of Stations
AUK	02 Oct 64	20 03 00.0	37.078N	116.009W	6
FORE	16 Jan 64	16 00 00.1	.142	.049	12
DUMONT	19 May 66	13 56 28.1	.111	.058	8
CHARTREUSE	06 May 66	15 00 00.1	.348	.322	7
TURF	24 Apr 64	20 10 00.2	.150	.055	10
KLICKITAT	20 Feb 64	15 30 00.1	.151	.040	9
PILEDRIVER	02 Jun 66	15 30 00.1	.227	.055	7
BRONZE	23 Jul 65	17 00 00.0	.098	.033	9
CORDUROY	03 Dec 65	15 13 02.1	.165	.052	9
BUFF	16 Dec 65	19 15 00.0	.073	.029	8
GREELEY	20 Dec 66	15 30 00.1	.302	.408	13
PIRANHA	13 May 66	13 30 00.0	.087	.034	9
NASH	19 Jan 67	16 45 00.1	.144	.136	7
BOURBON	20 Jan 67	17 40 04.1	.100	.004	4
AGILE	23 Feb 67	18 50 00.0	.127	.067	7
COMMODORE	20 May 67	15 00 00.2	.130	.064	5
SCOTCH	23 May 67	14 00 00.0	.275	.370	5
BILBY	13 Sep 63	17 00 00.1	.061	.022	14
TAN	03 Jan 66	14 00 00.0	.068	.035	8

TABLE II

Station Anomalies and Residuals

Station	Anomaly Relative to RK-ON Herrin 61	Herrin 66	JB	Residual Herrin 61	Event Key*
AD-IS	+1.11 sec	+0.04 sec	+0.57 sec	-1.1 sec	B
AX2AL	+2.21	+1.61	+2.23	+0.2	A
BE-FL	+1.11	+1.11	+1.15	-0.9	A
BL-WV	+0.66	+0.61	+0.84	-1.6	A
BR-PA	+0.74	+0.76	+0.84	-1.5	A
CP008	+1.51	+0.86	+1.55	-0.6	A
DH-NY	+0.09	+0.03	+0.11	-2.2	A
EB-MT	-0.84	+0.08	-0.68	-3.1	A
EN-MO	+0.08	+0.54	+0.04	-2.0	B
EU-AL	+2.66	+1.94	+2.71	+0.6	A
GG-GR	+1.06	+1.00	+2.07	-1.2	A
HN-ME	+1.11	+0.55	+0.97	-1.0	A
KC-MO	+1.71	+1.81	+1.45	-0.7	D
LV-LA	+1.51	+1.90	+1.48	-0.6	A
LZ-BV	+0.90	+0.94	+1.19	-1.9	A
NP-NT	+1.88	+0.96	+1.52	-0.2	A
OO-NW	-0.01	+0.01	+0.52	-2.4	A
PG-BC	+2.66	+2.94	+2.57	+0.3	C
PZ-PR	+2.28	+1.17	+1.53	+0.1	A
SI-BC	+1.87	+2.81	+2.05	-0.2	A
SV2QB	+0.35	-0.37	+0.16	-2.0	A**
SV3QB	+0.35	-0.37	+0.16	-2.0	A
WH2YK	+1.36	+1.13	+1.50	-0.8	C
RK-ON	0	0	0	-2.1	A

*A = Bilby-Tan
B = Bronze-Corduroy-Buff
C = Nash-Agile-Commodore
D = Gree ey

**Set equal to anomaly for SV3QB determined from A

TABLE III - Arrival Time Data

Event Reference Hour	Bilby 17	Tan 14	Auk 20	Fore 16	Dumont 14	Chartreuse 15	Turf 20	Klickitat 15	Piledriver 15	Bronze 17
STATION										
AD-IS										0812.2
AX2AL		0525.4			0153.6	0527.7			3525.5	
BE-FL		0607.2			0235.6		1548.9		3607.7	0548.4
BL-WV	0548.4			0548.9				3548.6		
BR-PA	0603.0			0603.3			1603.4	3603.1		0603.1
CPO	0521.6	0521.7	0821.9	0521.7	0149.9	0523.7	1522.1	3521.8	3521.8	0521.7
DH-NY	0626.7		0926.8				1627.3	3626.7		0626.7
EB-MT	0426.8			0426.4			1426.6	3426.5		
EN-MO										
EU-AL	0512.2			0512.6						
GG-GR	1221.9			1221.0			2222.7	4221.2		
HN-ME	0707.9	0708.1	1007.9	0707.8	0336.1	0708.8	1707.9	3707.9	3707.5	0707.9
KC-MO										
LV-LA	0441.1			0441.6						
LZ-BV	1111.0		1411.10				2111.6			
NP-NT	0731.5	0731.1	1031.3	0730.8	0358.7	0729.0	1730.6	3730.6	3729.9	0730.8
OO-NW	1131.8			1131.5						
PG-BC										
PZ-PR	0837.0			0838.1						
SI-BC		0428.5			0055.9	0424.4			3426.7	
SV2QB										0716.0
SV3QB		0716.5			0344.3	0716.2				
WH2YK										
RK-ON	0445.8	0445.9	0745.8	0445.4	0113.6	0445.2	1445.4	3445.1	3444.7	0445.5
	13	7	6	11	7	6	9	8	6	8

TABLE III (Continued)

Hour Reference Hour	Corduroy 15	Buff 19	Greeley 15	Bourbon 17	Agile 18	Nash 16	Commodore 15	Piranha 13	Scotch 14
STATION									
AD-IS	2113.9	2312.5							
AX2AL			3528.1					3525.7	
BE-FL	1909.5		3610.0					3607.6	
BL-WV									
BR-PA									
CPO	1823.8	2021.8	3524.2		5522.0	5022.7		3521.9	
DH-NY									
EB-MT									
EN-MO	1740.2	1938.0							
EU-AL			3515.0						
GG-GR			4221.2						
HN-ME	2009.6	2207.8	3709.0	4711.4	5708.1	5208.8	0708.1	3708.3	0709.2
KC-MO			3401.7						
LV-LA									
LZ-BV									
NP-NT	2032.5	2231.2	3729.2	4734.6	5730.8	5231.0		3731.3	
OO-NW			4130.7						
PG-BC			3403.6		5406.5	4906.7	0406.4	3407.5	0404.3
PZ-FR									
SI-BC	1729.5	1928.4						3428.4	
SV2QB									
SV3QB	2018.0	2216.5	3716.3	4719.9	5716.5	5216.7	0716.3	3716.5	0716.5
WH2YK			3536.8		5539.8	5039.4	0539.4		0537.7
RK-ON	1747.1	1945.7	3445.8	4449.1	5445.7	4946.2	0445 7	3445.8	0446.0
	8	7	12	3	6	6	4	8	4

TABLE IV

Location Errors when Neither Residuals nor Anomalies are Used

EVENT	NO. OF STATIONS	LOCATE-H61	SHIFT-H61	SHIFT-H66	SHIFT-JB
Buff	8	9.1	8.6	10.9	5.7
Turf	10	14.5	15.0	8.0	18.3
Corduroy	9	11.6	10.8	5.2	6.3
Nash	7	17.2	18.1	13.4	23.1
Bourbon	4	48.0	49.0	17.6	42.6
Piledriver	7	39.6	39.3	37.7	41.9
Bronze	9	13.3	13.1	8.5	12.3
Auk	6	7.1	7.2	3.7	4.8
Piranha	9	41.1	40.4	45.5	46.3
Fore	12	38.1	38.5	20.0	36.6
Greeley	13	10.1	12.3	11.6	25.5
Dumont	8	43.0	43.6	44.9	47.1
Chartreuse	7	60.0	59.8	48.5	62.8
Commodore	5	11.1	10.9	23.3	12.6
Agile	7	23.4	23.0	15.0	27.7
Scotch	5	17.4	17.8	26.6	19.6
Klickitat	9	33.5	33.7	12.8	38.2
Σ		438.1	441.1	353.2	471.4
Mean error, km		25.8	25.9	20.8	27.7

TABLE V

Location Errors When Residuals
or Anomalies are Used

EVENT	NO. OF STATIONS	LOCATE-H61	SHIFT-H61	SHIFT-H66	SHIFT-JB
Buff	8	2.4	0.1	0.3	0.2
Turf	10	0.5	0.1	0.2	0.1
Corduroy	9	1.6	1.0	0.9	0.9
Nash	7	5.8	1.7	1.4	1.8
Bourbon	4	2.8	1.9	2.1	1.9
Piledriver	7	2.0	2.9	1.5	3.3
Bronze	9	4.2	3.0	2.7	2.9
Auk	6	3.1	3.0	2.9	3.0
Piranha	9	0.8	3.1	2.7	3.2
Fore	12	3.3	3.2	2.9	3.1
Greeley	13	1.0	3.3	3.8	3.3
Dumont	8	2.2	3.4	3.0	3.4
Chartreuse	7	5.7	3.6	3.7	4.2
Commodore	5	4.1	3.7	3.2	3.3
Agile	7	1.5	3.9	2.4	3.1
Scotch	5	3.8	5.0	4.8	5.7
Klickitat	9	6.1	6.0	5.6	6.2
Σ		50.7	48.9	44.1	49.6
Mean error, km		2.98	2.86	2.59	2.92

TABLE VI

Actual Time Errors (Zero Mean) and Standard Deviations for all Events, With and Without Travel-Time Anomalies

Event		Time Errors	σ
Buff	a*	+0.15 +0.62 -0.96 -0.04 +0.94 +0.87 -0.59 -0.99	0.784
	b*	+0.01 +0.15 -0.11 -0.16 -0.02 +0.04 +0.11 -0.03	0.102
Turf	a	+0.03 +0.08 +0.78 -0.30 -1.48 +1.17 +0.24 -0.56 +0.94 -0.89	0.837
	b	+0.05 +0.02 -0.03 +0.29 -0.01 +0.79 -0.25 -0.27 -0.34 -0.25	0.336
Corduroy	a	+0.11 +0.22 +0.50 -0.90 -0.00 +0.89 +0.98 -0.68 -1.13	0.758
	b	-0.05 +0.11 +0.03 -0.01 -0.14 +0.01 +0.17 +0.00 -0.09	0.074
Agile	a	+0.23 -0.09 +0.58 +1.05 +0.21 -0.81 -1.19	0.777
	b	+0.00 +0.03 -0.09 -0.31 +0.17 +0.13 +0.06	0.160
Commodore	a	+0.25 +1.25 +0.10 -0.72 -0.89	0.858
	b	+0.15 -0.28 -0.11 +0.05 +0.19	0.194
Bourbon	a	+0.29 +0.98 -0.44 -0.82	0.800
	b	+0.00 -0.10 +0.88 +0.01	0.076
Piranha	a	+0.94 -0.10 +0.06 -0.20 +0.47 +1.14 +0.35 -1.17 -1.49	0.878
	b	+0.14 +0.18 -0.04 +0.11 -0.07 -0.04 -0.06 -0.10 -0.11	0.110
Greeley	a	+1.06 +0.09 +0.31 +1.35 -0.49 -0.21 +0.14 +0.76 -1.64 +1.48 -0.07 -1.39 -1.37	1.026
	b	+0.17 +0.27 +0.14 -0.01 -0.18 +0.05 -0.21 +0.18 -0.25 +0.21 -0.02 -0.32 -0.03	0.192
Nash	a	+0.26 +0.03 +0.68 +1.38 -0.06 -1.09 -1.19	0.917
	b	-0.04 +0.17 +0.03 +0.04 -0.13 -0.14 +0.08	0.111

TABLE VI (Continued)

Event		Time Errors	σ
Piledriver	a	+0.76 -0.08 +0.18 -0.33 +0.43 +0.49 -1.45	0.735
	b	-0.04 +0.20 +0.03 -0.03 -0.11 +0.02 -0.07	0.101
Bronze	a	+0.26 -0.15 +0.05 +0.74 -0.72 +0.36 +0.97 -0.66 -0.85	0.650
	b	-0.09 +0.02 +0.15 +0.10 +0.08 +0.08 -0.16 -0.00 -0.17	0.116
Dumont	a	+1.06 +0.11 +0.26 -0.08 +0.43 +0.54 -0.99 -1.34	0.797
	b	+0.07 +0.20 +0.02 +0.08 -0.25 -0.01 -0.06 -0.05	0.132
Chartreuse	a	+1.05 +0.25 +0.08 +0.63 +0.42 -1.02 -1.40	0.891
	b	+0.09 +0.00 +0.21 +0.02 -0.11 -0.07 -0.14	0.123
Auk	a	+0.90 -0.73 +0.17 -0.58 +1.00 -0.77	0.812
	b	+0.23 +0.20 -0.10 -0.13 -0.06 +0.04	0.131
Fore	a*	-0.14 -0.19 +0.25 -1.90 +1.69 -0.74 -0.05 +0.51 +0.88 -1.13 +1.93 -1.11	1.144
	b	+0.29 +0.16 -0.18 -0.02 +0.04 -0.72 -0.13 +0.01 -0.04 -0.06 +0.65 +0.00	0.318
Scotch	a	+0.10 +1.74 +0.50 -1.17 -1.16	1.225
	b	+0.07 +0.18 +0.26 -0.38 -0.12	0.256
Klickitat	a	+0.07 +0.12 +0.86 -0.57 -1.24 -0.06 +0.51 +1.18 -0.86	0.792
	b	+0.12 +0.09 +0.05 +0.06 +0.26 -0.41 +0.11 -0.07 -0.19	0.200

*a Errors computed without travel-time anomalies; Herrin 61 table

*b Errors computed with travel-time anomalies; Herrin 61 table.

TABLE VII

Confidence Regions
SHIFT-61

Event	Ellipse Areas km^2 Without anomalies a	With anomalies b	Improvement Factor, a/b	No. of Stations
Fore	2059*	348	6	12
Buff	2402	50	48	8
Chartreuse	1041*	131	8	7
Auk	10035	66	152	6
Bourbon	206088	7118	29	4
Dumont	1495	52	29	8
Agile	4020	234	17	7
Nash	7256	113	64	7
Commodore	27698	288	96	5
Greeley	2620	96	27	13
Klickitat	2384	202	12	9
Turf	2513	524	5	10
Piranha	2159	15	144	9
Scotch	37869	2309	16	5
Corduroy	1554	25	62	9
Bronze	2038	25	81	9
Piledriver	1593	79	20	7

*Confidence ellipse does not contain true epicenter.

TABLE VIII

02 13 80

RELATIVE TRAVEL-TIME ANOMALIES

(1) ERRINGEN TRAVEL-TIME TABLES (3) INCLUDING ELLIPTICITY (2) REFERENCE STATION MH-ON

(4) ANOMALY REGION = NEVADA TEST SITE

(5) DISTANCE RANGE = 2331 TO 2349 KM (6) AZIMUTH RANGE = 237.8 TO 238.9 DEGREES

(7) EVENT NAME	(8) DISTANCE	(9) AZIMUTH	(10) AU-IS (12)	AX2AL (11)	BE-FL	BL-WU	BR-PA	CPO	DH-NY	ER-MT	EN-MO	EU-AL
02 JUN66 PILEDRIVER	2331.29	238.16	0	1.529	1.208	0	0	.040	0	0	0	0
03 DEC65 CORDUROY	2336.19	238.03	.117	0	1.278	0	0	.073	0	0	.058	0
20 FEB64 KLICKITAT	2336.83	237.89	0	0	0	.607	1.005	1.002	.258	.512	0	0
06 MAY66 CHART	2337.46	238.02	0	1.060	0	0	0	1.400	0	0	0	0
24 APR64 TURF	2337.60	238.01	0	0	0	.875	.008	1.024	.544	.303	0	0
16 JAN64 FORE	2337.90	237.99	0	0	0	.031	.045	.718	0	.103	0	2.059
20 JAN67 BOURBON	2338.67	237.83	0	0	0	0	0	0	0	0	0	0
20 MAY67 COMMODORE	2339.78	237.80	0	0	0	0	0		0	0	0	0
23 FEB67 AGILE	2340.12	237.89	0	0	0	0	0	.700	0	0	0	0
23 JUL65 BRONZE	2340.56	237.88	.007	0	0	.600	.946	.046	.102	0	0	0
02 OCT64 AUK	2340.77	237.80	0	0	0	0	0	1.030	.012	0	0	0
19 MAY66 DUMONT	2340.00	237.88	0	1.771	1.307	0	0	.963	0	0	0	0
13 MAY66 PIRANHA	2341.53	237.86	0	1.007	1.342	0	0	.923	0	0	0	0
10 DEC65 BUFF	2342.38	237.82	.037	0	0	0	0	.040	0	0	.082	0
19 JAN67 NASH	2342.60	238.13	0	0	0	0	0	.830	0	0	0	0
13 SEP63 BILBY	2342.05	237.70	0	0	0	.607	.750	.877	.032	.005	0	1.035
03 JUN66 TAN	2343.15	237.83	0	1.610	1.110	0	0	.815	0	0	0	0
23 MAY67 SCOTCH	2346.30	238.78	0	0	0	0	0	0	0	0	0	0
20 DEC66 GREELEY	2346.39	238.87	0	1.896	1.417	0	0	1.110	0	0	0	1.070
	(13) AVERAGE		.054	1.746*	1.301*	.791*	.930*	.018*	.188	.258	.588	1.080*
	(14) SIGMA		.03	.185	.112	.145	.101	.107	.298	.209	.192	.034
	N (15)		3	6	6	5	5	16	5	4	2	3

EVENT NAME	DISTANCE	AZIMUTH	GG-GR	HN-ME	AC MO	LZ-HU	NP-NT	OA-HN	RG-RC	SI-PC	WH-YA	OU-ZOW
02 JUN66 PILEDRIVER	2331.29	238.16	0	.806	0	0	.877	0	0	2.802	0	0
03 DEC65 CORDUROY	2336.19	238.03	0	.510	0	0	1.430	0	0	3.048	0	-.201
20 FEB64 KLICKITAT	2338.63	237.89	.751	.773	0	0	1.450	0	0	0	0	0
06 MAY66 CHART	2337.46	238.02	0	.005	0	0	1.124	0	0	2.038	0	-.327
24 APR64 TURF	2337.60	238.01	2.008	.525	0	.002	.888	0	0	0	0	0
16 JAN64 FORE	2337.90	237.99	.314	.498	0	0	1.010	.005	0	0	0	0
20 JAN67 BOURBON	2338.67	237.83	0	.510	0	0	.827	0	0	0	0	-.328
20 MAY67 COMMODORE	2339.78	237.09	0	.540	0	0	0	0	2.520	0	.898	-.520
23 FEB67 AGILE	2340.12	237.80	0	.510	0	0	.805	0	2.028	0	1.249	-.318
23 JUL65 BRONZE	2340.58	237.88	0	.622	0	0	.809	0	0	0	0	0
02 OCT64 AUK	2340.77	237.80	0	.400	0	.755	.888	0	0	0	0	0
19 MAY66 DUMONT	2340.00	237.88	0	.670	0	0	.802	0	0	2.088	0	-.342
13 MAY66 PIRANHA	2341.53	237.80	0	.713	0	0	1.001	0	3.092	2.805	0	-.365
10 DEC65 BUFF	2342.30	237.82	0	.300	0	0	.880	0	0	2.818	0	-.700
19 JAN67 NASH	2342.60	238.13	0	.830	0	0	.822	0	2.088	0	.088	-.509
13 SEP63 BILBY	2342.05	237.70	.080	.512	0	.038	1.170	.000	0	0	0	0
03 JUN66 TAN	2343.12	237.83	0	.508	0	0	.750	0	0	2.807	0	-.374
23 MAY67 SCOTCH	2348.30	238.70	0	.000	0	0	0	0	3.170	0	1.408	-.802
20 DEC66 GREELEY	2345.39	238.87	.671	.578	1.085	0	1.216	-.104	3.090	0	1.193	-.809
	AVERAGE		.769*	.577*	1.085	.054*	.980*	-.000	2.803*	2.660*	1.139*	-.425*
	SIGMA		.828	.125	0	.001	.130	.110	.900	.080	.258	.150
	N		5	19	1	3	17	3	6	7	5	12

EVENT NAME	DISTANCE	AZIMUTH	SV20B	PZ-RR	LV-LA
02 JUN66 PILEDRIVER	2331.29	238.10	0	0	0
03 DEC65 CORDUROY	2336.19	238.03	0	0	0
20 FEB64 KLICKITAT	2336.63	237.89	0	0	0
06 MAY66 CHART	2337.46	238.02	0	0	0
24 APR64 TURF	2337.60	238.01	0	0	0
16 JAN64 FORE	2337.90	237.09	0	1.655	1.010
20 JAN67 BOURBON	2338.67	237.83	0	0	0
20 MAY67 COMMODORE	2339.78	237.80	0	0	0
23 FEB67 AGILE	2340.12	237.80	0	0	0
23 JUL65 BRONZE	2340.56	237.80	-.501	0	0
02 OCT64 AUK	2340.77	237.80	0	0	0
19 MAY66 DUMONT	2340.00	237.08	0	0	0
11 MAY66 PIRANHA	2341.53	237.86	0	0	0
10 DEC65 BUFF	2342.38	237.82	0	0	0
19 JAN67 NASH	2342.08	238.13	0	0	0
13 SEP63 BILBY	2342.05	237.70	0	1.167	1.002
03 JUN66 TAN	2343.12	237.83	0	0	0
23 MAY67 SCOTCH	2346.30	238.70	0	0	0
20 DEC66 GREELEY	2346.30	238.87	0	0	0
	AVERAGE		-.501	1.511	1.010*
	SIGMA		0	.207	.012
	N		1	2	2

* INDICATES ANOMALY AVERAGE IS SIGNIFICANTLY NON-ZERO AT 95 PERCENT

EVENT PARAMETERS

(16) 18 EPICENTERS	(17) LATITUDE	(18) LONGITUDE	(19) DEPTH	(20) ORIGIN TIME	EPOCH SIGMA (21)	(22) REF STAB	(23) BIAS SIGMA	(24) NO. STA
02 JUN66 PILEDRIVER	37.227	-116.055	0	15 30 00.1	.1100	.000	.002	8
03 DEC65 CORDUROY	37.165	-116.052	0	15 13 00.1	.1113	-.007	.005	5
20 FEB64 KLICKITAT	37.151	-116.040	0	15 30 00.1	.1733	-.004	.147	5
06 MAY66 CHART	37.340	-116.322	0	15 00 00.1	.1001	-.120	.104	8
24 APR64 TURF	37.150	-116.055	0	21 10 00.2	.3074	-.171	.343	8
16 JAN64 FORE	37.142	-116.040	0	16 00 00.3	.0027	.040	.208	11
20 JAN67 BOURBON	37.100	-116.004	0	17 40 04.1	.1202	.025	.114	3
20 MAY67 COMMODORE	37.130	-116.084	0	15 00 00.1	.2091	.204	.100	4
23 FEB67 AGILE	37.127	-116.000	0	18 50 00.0	.1732	.070	.155	8
23 JUL65 BRONZE	37.000	-116.033	0	17 00 00.0	.0731	.030	.089	5
02 OCT64 AUK	37.070	-116.000	0	20 03 00.0	.1587	.002	.114	5
19 MAY66 DUMONT	37.111	-116.000	0	13 56 28.1	.0001	-.020	.400	7
13 MAY66 PIRANHA	37.007	-116.034	0	13 30 00.0	.0805	-.054	.008	8
10 DEC65 BUFF	37.073	-116.020	0	19 15 00.0	.1111	.023	.108	7
19 JAN67 NASH	37.144	-116.135	0	16 45 00.1	.1144	.054	.097	4
13 SEP63 BILBY	37.001	-116.023	0	17 00 00.1	.1900	.003	.140	13
03 JUN66 TAN	37.000	-116.035	0	14 00 00.0	.1394	.405	.005	7
23 MAY67 SCOTCH	37.278	-116.370	0	14 00 00.0	.3920	-.118	.271	4
20 DEC66 GREELEY	37.302	-116.408	0	15 30 00.1	.1514	-.031	.150	12

TABLE IX

02 12 68

RELATIVE TRAVEL-TIME ANOMALIES

J-B TRAVEL-TIME TABLES INCLUDING ELLIPTICITY REFERENCE STATION MR-ON

ANOMALY REGION - NEVADA TEST SITE
DISTANCE RANGE - 2331 TO 2346 KM AZIMUTH RANGE - 237.8 TO 238.8 DEGREES

EVENT NAME	DISTANCE	AZIMUTH	AU-10	4X24L	OE-7L	BL-WB	BR-P4	BPD00	BH-NT	ED-NT	BN-MO	BU-AL
02 JUN66 PILEDRIVER	2331.29	238.16	0	2.287	1.363	0	0	1.600	0	0	0	0
03 DEC65 CORDUROY	2334.19	238.03	.069	0	1.342	0	0	1.700	0	0	.173	0
20 JUL64 KLICKITAT	2330.63	237.90	0	0	0	1.152	1.122	1.709	.342	-.216	0	0
06 MAY66 CHART	2337.40	238.82	0	2.492	0	0	0	1.477	0	0	0	0
24 APR64 TURF	2337.80	238.01	0	0	0	1.134	1.106	1.742	.091	-.438	0	0
16 JAN64 FORE	2337.90	237.90	0	0	0	1.105	1.004	1.420	0	-.022	0	2.807
20 JAN67 BOURBON	2338.07	237.83	0	0	0	0	0	0	0	0	0	0
20 MAY67 COMMODORE	2339.70	237.90	0	0	0	0	0	0	0	0	0	0
23 FEB67 AGILE	2340.15	237.89	0	0	0	0	0	1.408	0	0	0	0
23 JUL65 BRONZE	2340.50	237.80	.538	0	0	.013	1.042	1.654	.193	0	0	0
02 OCT64 AUK	2340.77	237.00	0	0	0	0	0	1.740	.143	0	0	0
19 MAY66 DUMONT	2340.89	237.94	0	2.395	1.442	0	0	1.663	0	0	0	0
13 MAY66 PIRANHA	2341.53	237.86	0	2.432	1.206	0	0	1.624	0	0	0	0
16 DEC65 DUFF	2342.38	237.82	.540	0	0	0	0	1.670	0	0	0	0
19 JAN67 NASH	2342.08	238.13	0	0	0	0	0	1.915	0	0	-.039	0
13 SEP63 BILBY	2342.95	237.79	0	0	0	.046	.029	1.572	.111	-.003	0	2.708
03 JUN66 TAN	2343.15	237.83	0	2.220	1.146	0	0	1.027	0	0	0	0
23 MAY67 SCOTCH	2346.38	238.76	0	0	0	0	0	0	0	0	0	0
20 DEC66 GREELEY	2346.39	238.87	0	2.431	1.400	0	0	1.720	0	0	0	2.751
	AVERAGE		.502*	2.250*	1.340*	1.046*	1.023*	1.630*	.208	-.408*	.069	2.726*
	SIGMA		.075	.111	.105	.150	.114	.104	.230	.219	.147	.040
	N		3	6	6	5	5	10	5	4	2	2

EVENT NAME	DISTANCE	AZIMUTH	DU-GO	HN-MZ	NC MO	LZ-OV	NP-NT	OD-NW	PO-BC	BI-RC	WMZ7N	ZV300
02 JUN66 PILEDRIVER	2321.29	238.16	0	.962	0	0	1.901	0	0	2.109	0	0
03 DEC65 CORDUROY	2336.19	238.03	0	.970	0	0	1.632	0	0	2.325	0	.308
20 FOR64 KLICKITAT	2330.63	227.90	1.044	1.221	0	0	1.654	0	0	0	0	0
06 MAY66 CHART	2337.46	228.82	0	1.323	0	0	1.709	0	0	2.106	0	.237
24 APR64 TURF	2337.60	238.01	3.007	.070	0	1.177	1.430	0	0	0	0	0
16 JAN64 FORE	2337.90	237.99	1.404	.009	0	0	1.590	.935	0	0	0	0
20 JAN67 BOURBON	2338.07	227.83	0	.906	0	0	1.413	0	0	0	0	.237
20 MAY67 COMMODORE	2339.70	237.99	0	.904	0	0	0	0	2.164	0	1.212	.020
22 FEB67 AGILE	2340.15	227.90	0	.944	0	C	1.302	0	2.245	0	1.025	.232
23 JUL65 BRONZE	2340.50	237.00	0	1.053	0	0	1.424	0	0	0	0	0
02 OCT64 AUK	2340.77	237.00	0	.029	0	1.024	1.425	0	0	0	0	0
19 MAY66 DUMONT	2340.89	237.84	0	1.101	0	0	1.379	0	0	2.007	0	.204
13 MAY66 PIRANHA	2341.53	237.86	0	1.140	0	0	1.572	0	2.084	2.056	0	.170
16 DEC65 DUFF	2342.38	237.82	0	.709	0	0	1.533	0	0	2.004	0	.290
19 JAN67 NASH	2342.00	238.13	0	1.064	0	0	1.404	0	2.975	0	1.353	-.090
13 SEP63 BILBY	2342.05	237.70	2.000	.932	0	1.103	1.725	.910	0	0	0	0
03 JUN66 TAN	2343.15	237.83	0	1.008	0	0	1.213	0	0	2.240	0	.103
23 MAY67 SCOTCH	2346.20	238.76	0	1.103	0	0	0	0	2.769	0	1.058	-.150
20 DEC66 GREELEY	2346.39	238.87	1.017	1.002	1.302	0	1.727	.209	2.714	0	1.409	-.176
	AVERAGE		2.065*	1.013*	1.302	1.122*	1.526*	.447*	2.532*	2.135*	1.300*	.121*
	SIGMA		.620	.120	0	.003	.130	.137	.250	.102	.240	.107
	N		5	10	1	3	17	3	6	7	5	12

EVENT NAME	DISTANCE	AZIMUTH	OVZDO	22-PR	LB-L4
02 JUN66 PILEDRIVER	2321.29	228.16	0	0	0
03 DEC65 CORDUROY	2236.19	238.03	0	0	0
20 DEC64 KLICKITAT	2330.63	237.00	0	0	0
06 MAY66 CHART	2337.46	238.82	0	0	0
24 APR64 TURF	2137.00	238.01	0	0	0
16 JAN64 FORE	2327.00	237.89	0	2.243	1.542
20 JAN67 BOURBON	2338.07	227.83	0	0	0
20 MAY67 COMMODORE	2339.70	237.00	0	0	0
23 FEB67 AGILE	2340.15	237.90	0	0	0
23 JUL65 BRONZE	2340.56	227.00	.047	0	0
02 OCT64 AUK	2340.77	227.80	0	0	0
19 MAY66 DUMONT	2340.59	237.94	0	0	0
13 MAY66 PIRANHA	2341.53	237.86	0	0	0
16 DEC65 DUFF	2342.38	227.02	0	0	0
19 JAN67 NASH	2342.00	238.13	0	0	0
13 SEP63 BILBY	2342.05	227.75	0	1.933	4.479
03 JUN66 TAN	2343.15	237.03	0	0	0
23 MAY67 SCOTCH	2346.30	238.76	0	0	0
20 DEC66 GREELEY	2346.39	238.87	0	0	0
	AVERAGE		.047	1.004	1.510*
	SIGMA		0	.902	.049
	N		1	2	2

* INDICATES ANOMALY AVERAGE IS SIGNIFICANTLY NON-ZERO AT 95 PERCENT

EVENT PARAMETERS

ID EPICENTERS	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME	SHOCN SIGMA	REF BIAS	BIAS SIGMA	NO. STA
02 JUN66 PILEDRIVER	37.227	-116.025	0	15 20 00.1	.0002	.017	.070	0
03 DEC65 CORDUROY	37.165	-116.052	0	15 12 02.1	.1293	-.007	.004	0
20 DEC64 KLICKITAT	37.151	-116.040	0	15 30 00.1	.1020	-.102	.140	0
06 MAY66 CHART	37.340	-116.322	0	19 00 00.1	.1703	-.120	.106	6
24 APR64 TURF	37.190	-116.059	0	20 10 20.2	.3039	-.102	.343	9
16 JAN64 FORE	37.142	-116.040	0	16 00 00.1	.2600	.034	.290	11
20 JAN67 BOURBON	37.100	-116.004	0	17 40 24.1	.1217	.010	.140	3
20 MAY67 COMMODORE	37.130	-116.064	0	15 00 00.1	.2790	.190	.162	4
23 FEB67 AGILE	37.127	-116.046	0	10 50 00.0	.1704	.067	.154	6
23 JUL65 BRONZE	37.090	-116.033	0	17 00 00.0	.0763	.030	.064	0
02 OCT64 AUK	37.070	-116.000	0	20 03 00.0	.1971	.090	.110	0
19 MAY66 DUMONT	37.111	-116.050	0	13 56 20.1	.0010	-.010	.000	7
13 MAY66 PIRANHA	37.007	-116.034	0	13 20 00.0	.0013	-.050	.074	0
16 DEC65 DUFF	37.073	-116.020	0	10 15 00.0	.1103	.027	.112	7
19 JAN67 NASH	37.144	-116.135	0	16 45 00.1	.1220	.067	.089	6
13 SEP63 BILBY	37.061	-116.022	0	17 00 00.1	.1601	.077	.140	13
02 JUN66 TAN	37.069	-116.039	0	14 00 00.0	.1442	.101	.004	7
22 MAY67 SCOTCH	37.275	-116.370	0	14 00 00.0	.3035	-.105	.270	4
20 DEC66 GREELEY	37.302	-116.408	0	18 30 20.0	.1473	-.400	.147	12

TABLE X

02 13 68 RELATIVE TRAVEL-TIME ANOMALIES

HERRIN 68 TRAVEL-TIME TABLES INCLUDING ELLIPTICITY — REFERENCE STATION NK-ON

ANOMALY REGION = NEVADA TEST SITE
DISTANCE RANGE = 2331 TO 2340 KM AZIMUTH RANGE = 237.0 TO 228.0 DEGREES

EVENT NAME	DISTANCE	AZIMUTH	BO-IB	AXZOL	HE-FL	BL-HV	OB-P4	CPO	DN-NT	OB-MT	ON-NO	OU-OL
02 JUN66 PILEDRIVER	2331.29	238.10	0	2.100	1.320	0	0	1.656	0	0	0	0
03 DEC65 CORDUROY	2330.19	238.03	1.206	0	1.306	0	0	1.661	0	0	.284	0
08 FEB64 KLICKITAT	2336.63	237.80	0	0	0	.068	1.025	1.748	.339	-.206	0	0
06 MAY66 CHART	2337.40	238.42	0	2.439	0	0	0	1.653	0	0	0	0
24 APR64 TURF	2337.60	238.01	0	0	0	.950	1.811	1.704	.609	-.590	0	0
16 JAN64 FORE	2337.80	237.98	0	0	0	1.005	.056	1.386	0	-.798	0	2.755
08 JAN67 BOURBON	2338.07	237.63	0	0	0	0	0	0	0	0	0	0
20 MAY67 COMMODORE	2339.78	237.88	0	0	0	0	0	0	0	0	0	0
23 FEB67 AGILE	2340.12	237.98	0	0	0	0	0	1.452	0	0	0	0
23 JUL65 BRONZE	2340.56	237.80	1.075	0	0	.730	.047	1.015	.172	0	0	0
02 OCT64 AUK	2340.77	237.80	0	0	0	0	0	1.698	.081	0	0	0
19 MAY66 DUMONT	2340.89	237.84	0	2.378	1.400	0	0	1.025	0	0	0	0
13 MAY66 PIRANHA	2341.53	237.86	0	2.410	1.350	0	0	1.585	0	0	0	0
10 DEC65 BUFF	2342.30	237.82	1.096	0	0	0	0	1.438	0	0	-.003	0
19 JAN67 NASH	2342.06	238.13	0	0	0	0	0	1.402	0	0	0	0
13 SEP63 BILBY	2342.89	237.78	0	0	0	.657	.744	1.533	.800	-.026	0	2.650
03 JUN66 TAN	2343.12	237.83	0	2.011	1.116	0	0	1.488	0	0	0	0
03 MAY67 SCOTCH	2340.30	238.76	0	0	0	0	0	0	0	0	0	0
20 DEC66 GREELEY	2340.39	238.87	0	2.416	1.414	0	0	1.700	0	0	0	2.009
	AVERAGE		1.126*	2.341*	1.320*	.062*	.837*	1.602*	.262	-.655*	.108	2.098*
	SIGMA		.070	.112	.111	.150	.113	.105	.238	.208	.147	.050
	N		3	6	6	8	5	14	5	4	2	2

EVENT NAME	DISTANCE	AZIMUTH	GG-GN	NN-ME	KC MO	LZ-BV	NP-NT	OD-NN	PO-BC	SI-BC	WN-YB	OU-ZO
02 JUN66 PILEDRIVER	2331.29	238.10	0	1.102	0	0	1.842	0	0	1.901	0	0
03 DEC65 CORDUROY	2330.19	238.03	0	1.112	0	0	1.981	0	0	2.120	0	.404
20 FEB64 KLICKITAT	2336.63	237.80	.037	1.363	0	0	2.003	0	0	0	0	0
06 MAY66 CHART	2337.46	238.82	0	1.484	0	0	2.047	0	0	1.086	0	.415
24 APR64 TURF	2337.60	238.01	2.000	1.112	0	.874	1.787	0	0	0	0	0
10 JAN64 FORE	2337.90	237.80	.365	1.041	0	0	1.848	.011	0	0	0	0
20 JAN67 BOURBON	2338.67	227.83	0	1.099	0	0	1.766	0	0	0	0	.415
20 MAY67 COMMODORE	2338.76	227.88	0	1.127	0	0	0	0	0.100	0	1.004	.205
23 FEB67 AGILE	2340.15	227.89	0	1.086	0	0	1.734	0	0.200	0	1.477	.412
22 JUL65 BRONZE	2340.56	237.00	0	1.196	0	0	1.778	0	0	0	0	0
08 OCT64 AUK	2340.77	237.80	0	.972	0	.731	1.789	0	0	0	0	0
19 MAY66 DUMONT	2340.90	237.94	0	1.243	0	0	1.728	0	0	1.904	0	.305
13 MAY66 PIRANHA	2341.53	227.86	0	1.283	0	0	1.827	0	0.008	1.871	0	.360
10 DEC65 BUFF	2342.30	237.82	0	.932	0	0	1.889	0	0	1.803	0	.431
19 JAN67 NASH	2342.00	224.12	0	1.266	0	0	1.838	0	0.624	0	1.208	.132
13 SEP63 BILBY	2342.99	237.79	1.058	1.875	0	.980	2.092	-.010	0	0	0	0
03 JUN66 TAN	2343.10	237.82	0	1.147	0	0	1.479	0	0	1.890	0	.048
23 MAY67 SCOTCH	2340.20	228.76	0	1.244	0	0	0	0	2.050	0	1.734	.028
20 DEC66 GREELEY	2348.39	228.87	.910	1.144	1.525	0	2.085	-.231	2.803	0	1.278	.011
	AVERAGE		1.050*	1.105*	1.525	.835*	1.876*	-.077	2.611*	1.831*	1.272*	.202*
	SIGMA		.020	.106	0	.091	.133	.123	.211	.092	.257	.105
	N		5	10	1	3	17	3	4	7	8	12

EVENT NAME	DISTANCE	AZIMUTH	OU-ZU	PZ-BR	LV-LO
02 JUN66 PILEDRIVER	2331.29	238.10	0	0	0
03 DEC65 CORDUROY	2330.19	238.03	0	0	0
20 FEB64 KLICKITAT	2336.63	237.89	0	0	0
06 MAY66 CHART	2337.46	238.82	0	0	0
24 APR64 TURF	2337.60	238.01	0	0	0
16 JAN64 FORE	2337.99	237.99	0	2.004	1.570
20 JAN67 BOURBON	2338.07	237.83	0	0	0
20 MAY67 COMMODORE	2339.78	227.99	0	0	0
23 FEB67 AGILE	2340.15	237.89	0	0	0
23 JUL65 BRONZE	2340.50	237.00	.220	0	0
02 OCT64 AUK	2340.77	237.80	0	0	0
19 MAY66 DUMONT	2340.99	237.94	0	0	0
13 MAY66 PIRANHA	2341.53	237.86	0	0	0
10 DEC65 BUFF	2342.30	237.80	0	0	0
19 JAN67 NASH	2342.00	228.13	0	0	0
13 SEP63 BILBY	2340.05	227.70	0	2.201	1.500
03 JUN66 TAN	2343.10	237.03	0	0	0
23 MAY67 SCOTCH	2340.30	238.76	0	0	0
20 DEC66 GREELEY	2340.39	238.87	0	0	0
	AVERAGE		.220	2.036	1.530*
	SIGMA		0	.504	.044
	N		1	0	2

* INDICATES ANOMALY AVERAGE IS SIGNIFICANTLY NON-ZERO AT 95 PERCENT

EVENT PARAMETERS

ID EPICENTERS	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME	SHOCK SIGMA	REF BIAS	BIAS SIGMA	NO. STA
02 JUN66 PILEDRIVER	37.227	-116.055	0	15 30 00.1	.0793	.025	.074	6
03 DEC65 CORDUROY	37.105	-116.002	0	15 13 00.1	.1220	-.004	.084	8
08 FEB64 KLICKITAT	37.151	-116.040	0	15 20 00.1	.1002	-.100	.149	8
06 MAY66 CHART	37.340	-116.322	0	15 00 00.1	.1725	-.117	.115	8
24 APR64 TURF	37.150	-116.055	0	20 10 00.0	.3933	-.181	.343	9
16 JAN64 FORE	37.142	-116.040	0	14 00 00.1	.2615	.023	.256	11
20 JAN67 BOURBON	37.100	-116.004	0	17 40 04.1	.1100	.010	.017	3
20 MAY67 COMMODORE	37.130	-116.064	0	15 00 00.1	.3042	.012	.180	4
23 FEB67 AGILE	37.127	-116.006	0	18 00 00.0	.1002	.077	.104	9
22 JUL65 BRONZE	37.090	-116.033	0	17 00 00.0	.0702	.039	.082	8
02 OCT64 AUK	37.070	-116.009	0	00 02 00.0	.1000	.094	.114	8
19 MAY66 DUMONT	37.111	-116.006	0	13 50 20.1	.0005	-.021	.080	7
13 MAY66 PIRANHA	37.087	-116.034	0	12 30 00.0	.0741	-.043	.050	8
16 DEC65 BUFF	37.073	-116.029	0	18 15 00.0	.1100	.032	.112	7
19 JAN67 NASH	37.144	-116.135	0	16 40 00.1	.1022	.072	.080	9
13 SEP63 BILBY	37.001	-116.022	0	17 00 00.1	.1070	.078	.140	12
03 JUN66 TAN	37.006	-116.035	0	14 00 00.0	.1429	.000	.096	7
22 MAY67 SCOTCH	37.275	-116.370	0	14 00 00.0	.3241	-.131	.290	4
20 DEC66 GREELEY	37.302	-116.408	0	18 30 00.1	.1001	-.010	.161	12

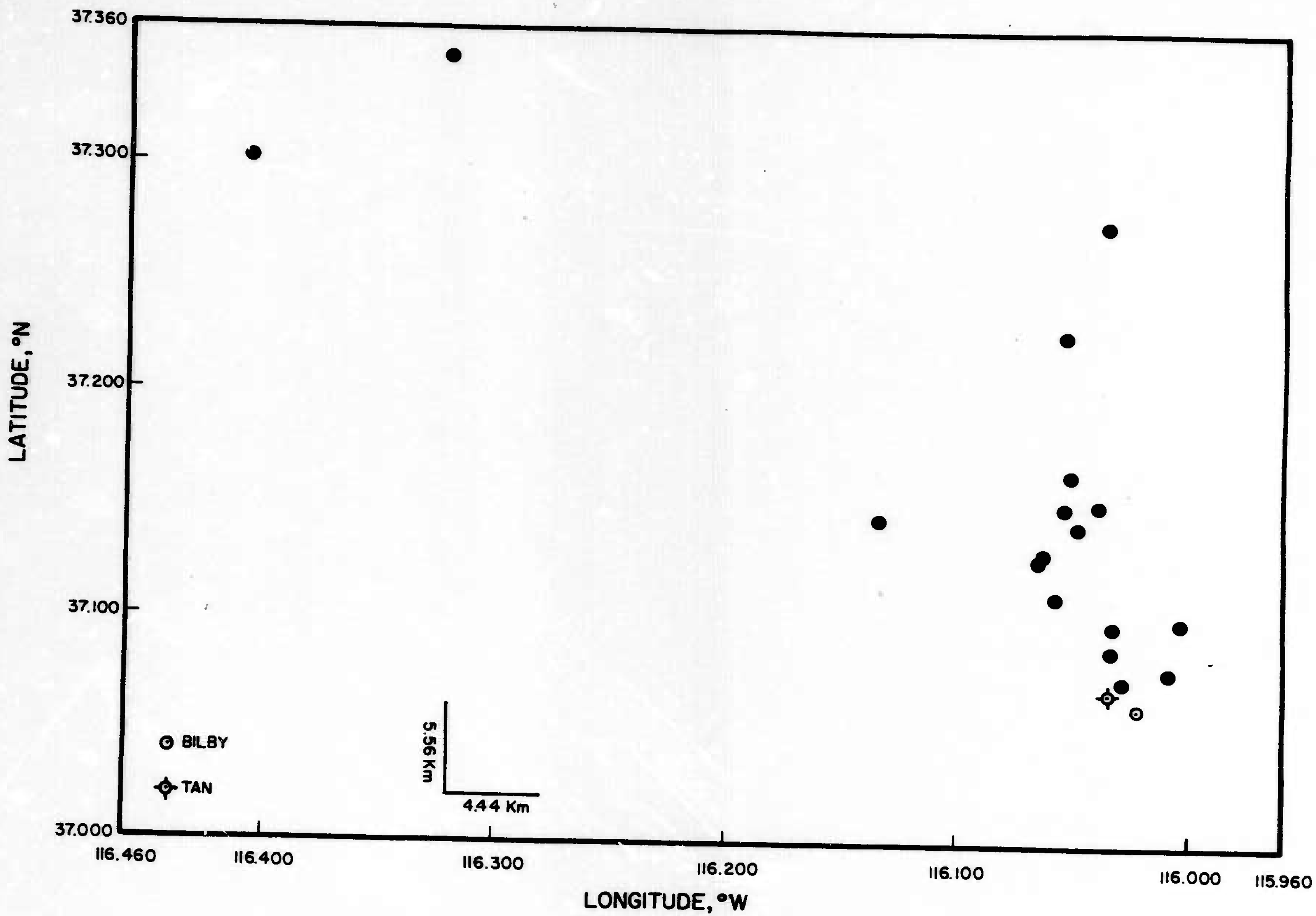


Figure 1. Nevada Test Site Area

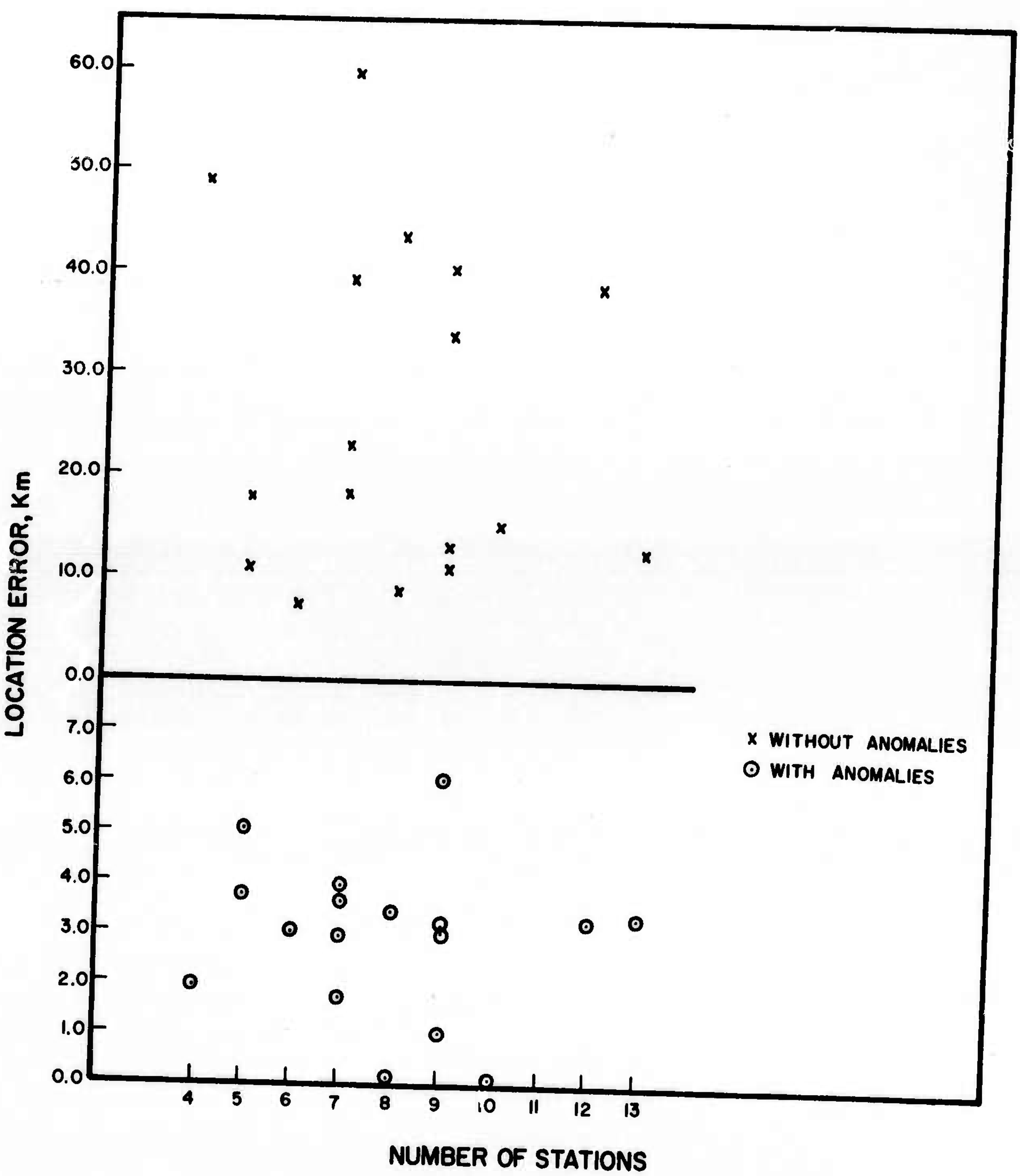


Figure 2. Location error vs number of recording stations

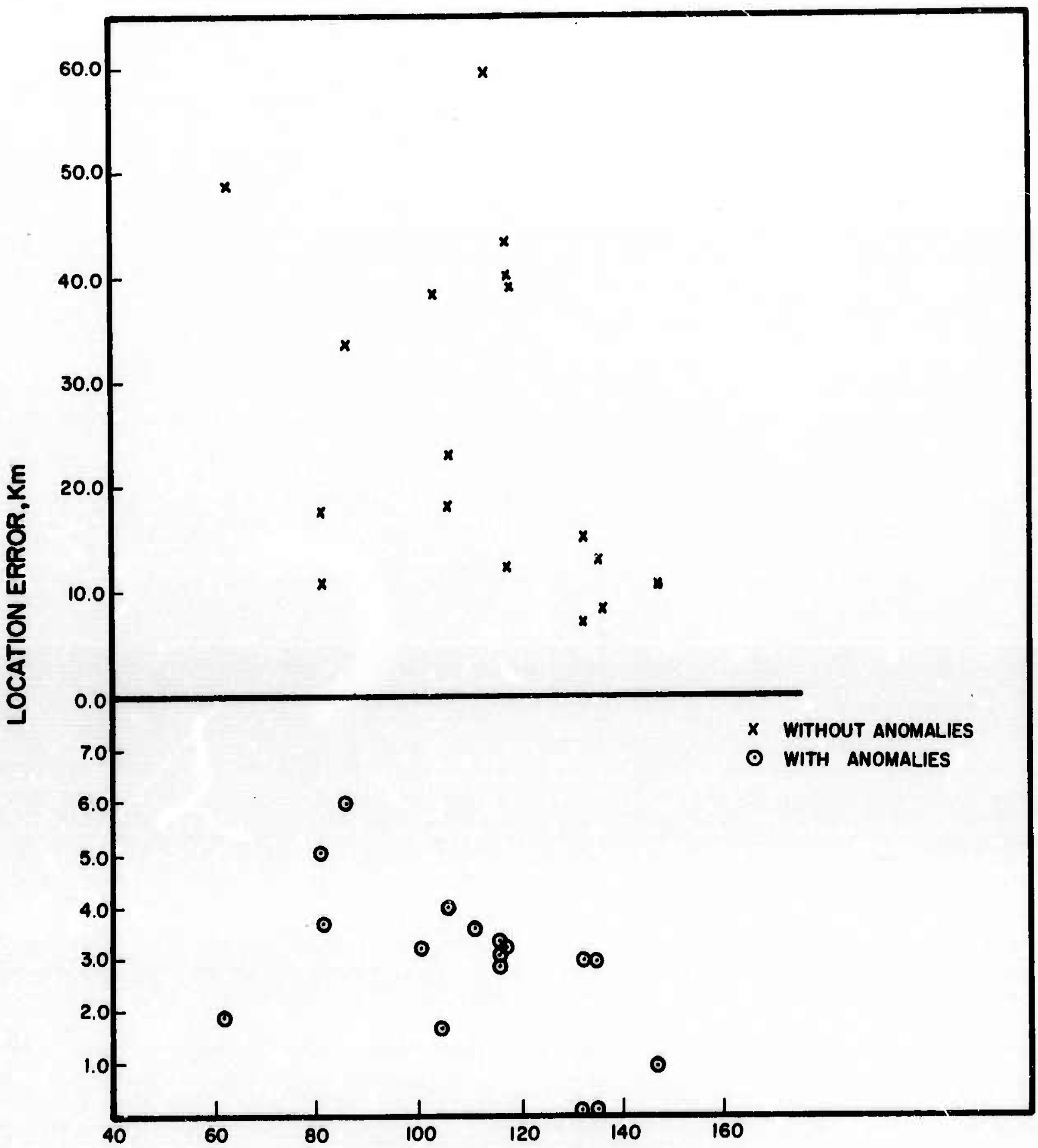


Figure 3. Location error vs azimuth aperture

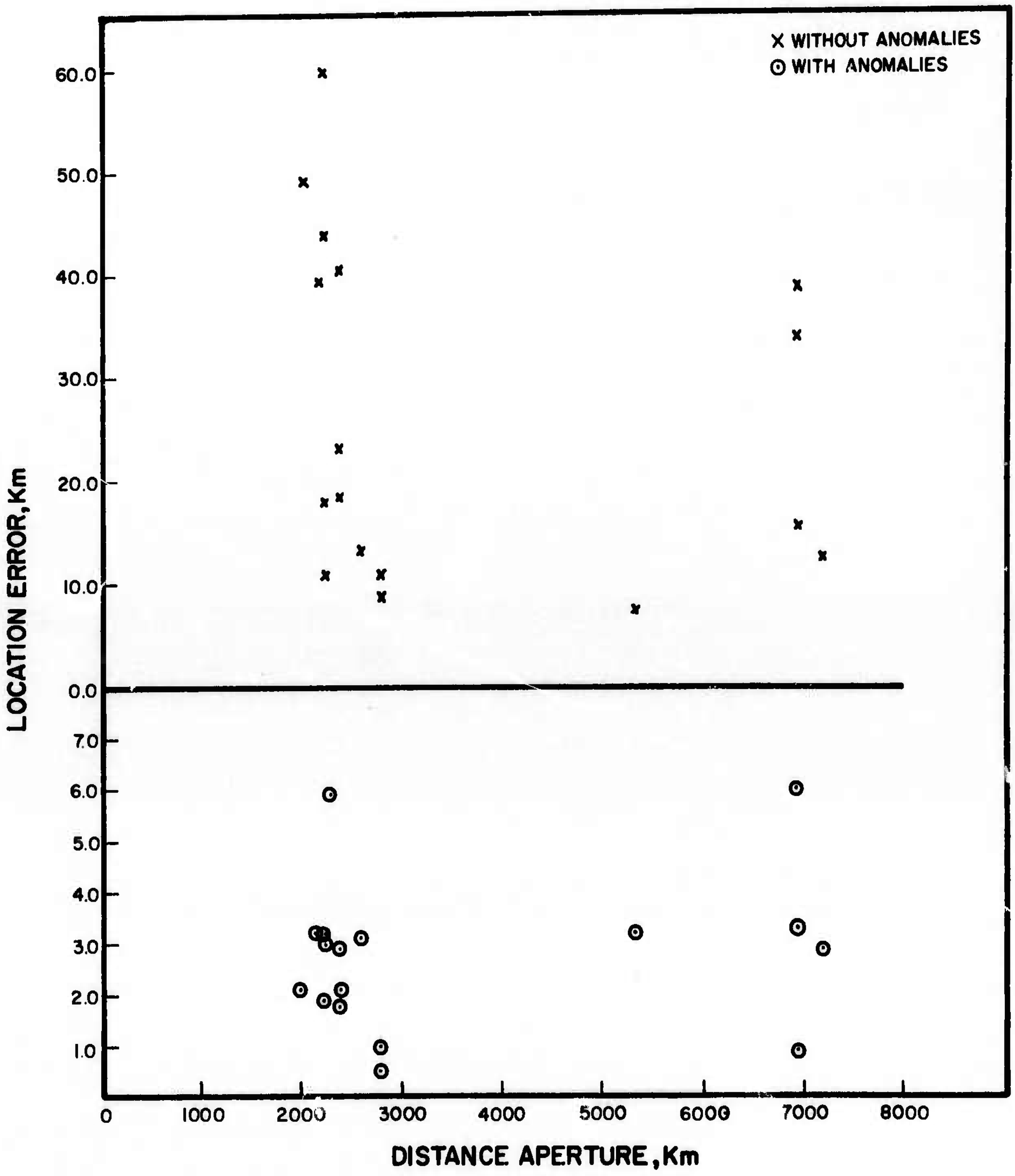


Figure 4. Location error vs distance aperture

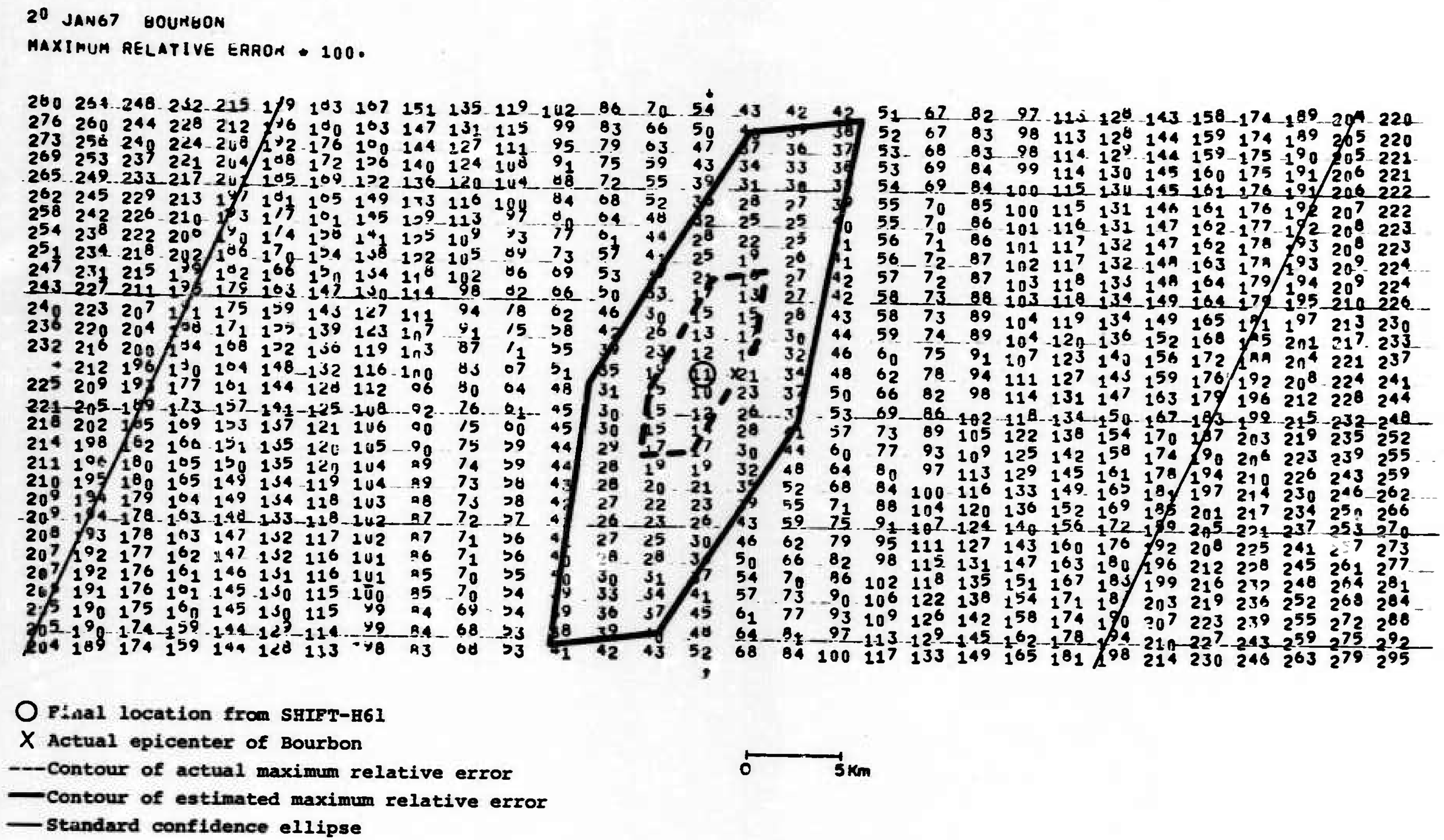
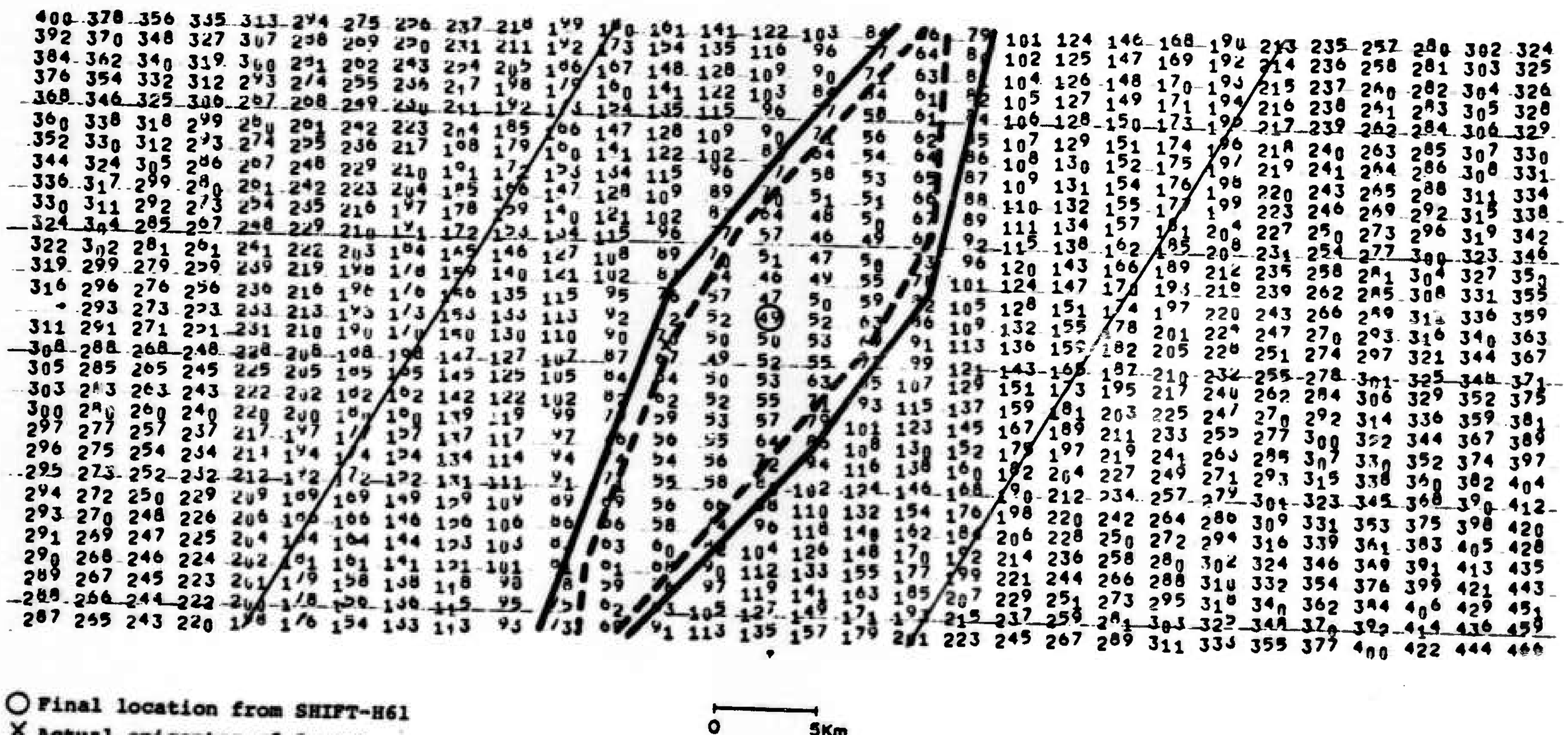


Figure 5. Maximum-relative-error output from SIGRID; event Bourbon

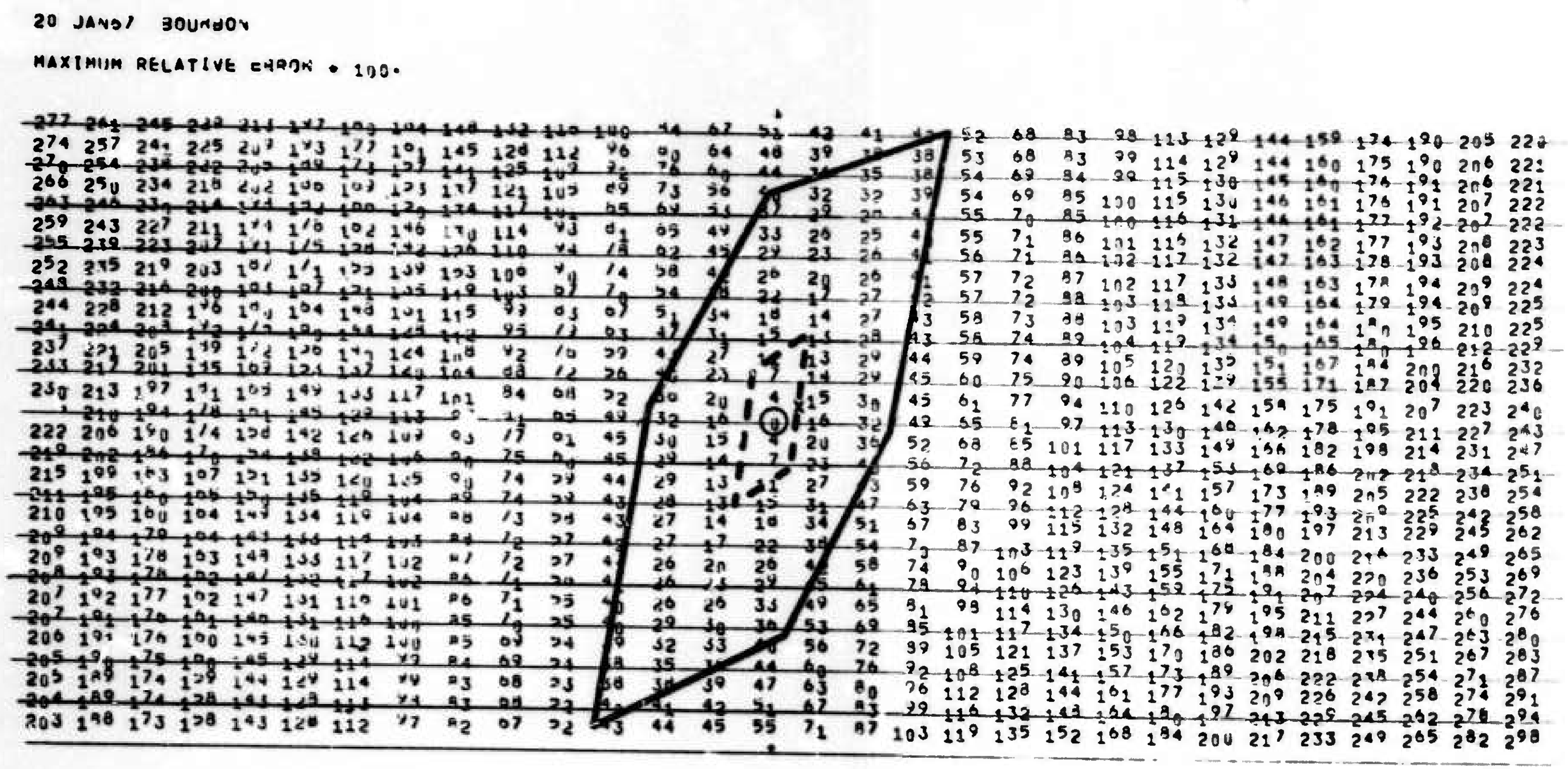
23 MAY67 SCOTCH

MAXIMUM RELATIVE ERROR * 100.



○ Final location from SHIFT-H61
× Actual epicenter of Scotch
--- Contour of actual maximum relative error
— Contour of estimated maximum relative error
— Standard confidence ellipse

Figure 6. Maximum-relative-error output from SIGRID; event Scotch



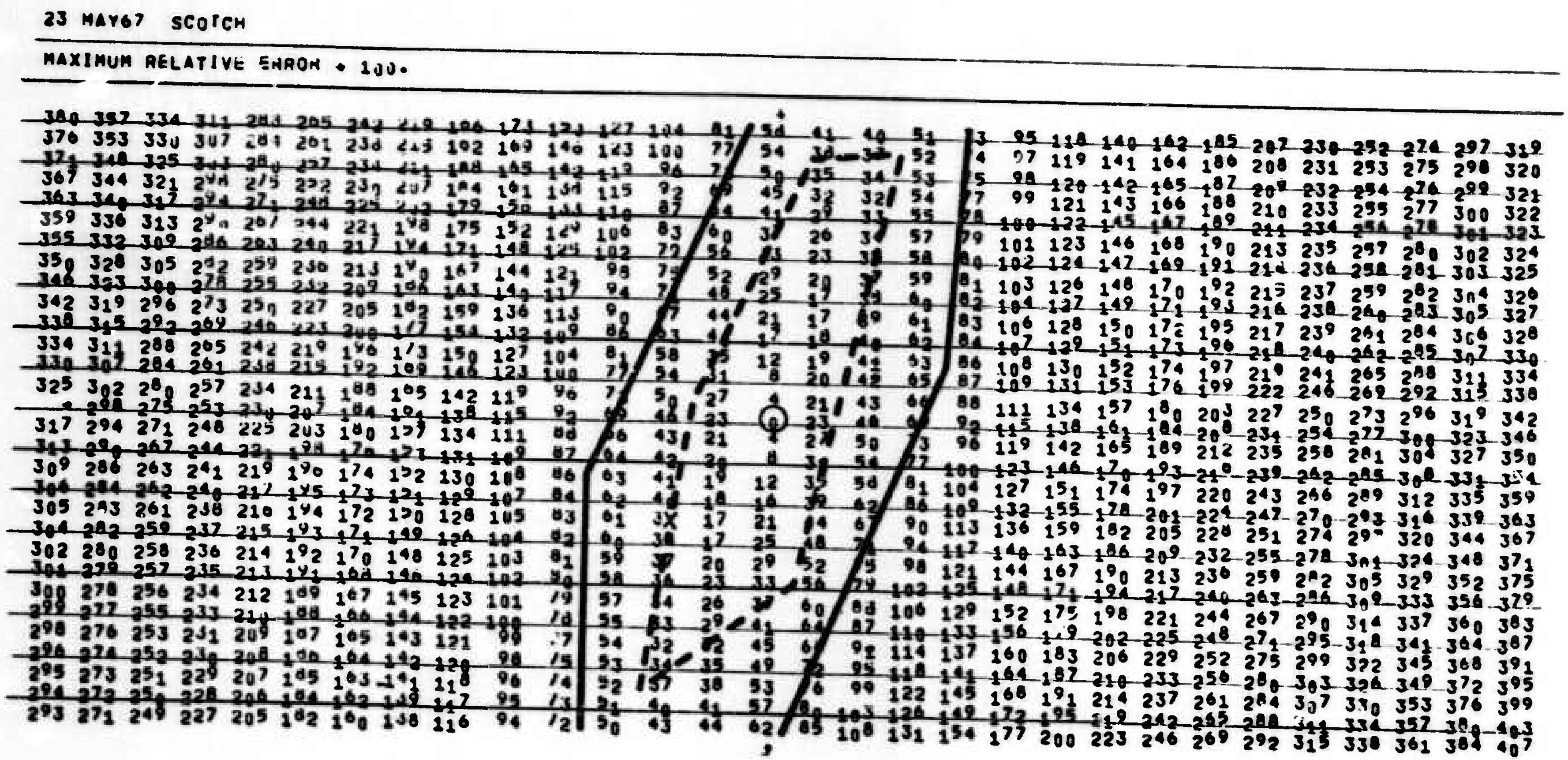
○ Final location from SHIFT-H61

X Actual epicenter of Bourbon

--- Contour of actual maximum relative error

— Contour of estimated maximum relative error

Figure 7. Maximum-relative-error output from SIGRID; event Bourbon with three stations



○ Final location from SHIFT-H61

X Actual epicenter of Scotch

---Contour of actual maximum relative error

——Contour of estimated maximum relative error

Figure 8. Maximum-relative error output from SIGRID; event Scotch with three stations

02 07 68 20 JAN67 BOURBON HERRING61 TRAVEL TIME TABLES

REFERENCE LATITUDE	37.0997 ON LINE	15
LONGITUDE	-116.0238 IN COLUMN	15
DEPTH	0	

	UPPER LEFT	LOWER LEFT	INCREMENT DEG	INCREMENT ARC KM	UPPER RIGHT	LOWER RIGHT
LATITUDE	37.2256	36.9648	.0090	1.00	37.2256	36.9648
LONGITUDE	-116.4047	-116.4047	.0271	2.40	-115.6190	-115.6190

STANDARD DEVIATION OF ERRORS * 100.

123	115	108	100	93	85	78	71	63	56	49	42	35	29	24	19	17	19	23	28	34	41	48	55	62	70	77	84	92	99
121	114	106	99	92	84	77	69	62	55	48	41	34	28	22	18	16	18	23	28	35	42	49	56	63	70	78	85	93	100
120	113	105	98	90	83	75	68	61	53	46	39	32	26	20	16	15	18	23	29	35	42	49	57	64	71	79	86	94	101
119	111	104	96	89	82	74	67	59	52	45	38	31	24	19	15	14	17	23	29	36	43	50	57	65	72	80	87	95	102
118	110	103	95	88	80	73	65	58	51	43	36	29	23	17	13	13	17	23	29	36	44	51	58	66	73	81	88	96	103
116	109	101	94	86	79	71	64	57	49	42	35	28	21	16	12	13	17	23	30	37	44	52	59	67	74	81	89	96	104
115	108	100	93	85	78	70	63	55	48	41	33	26	20	14	11	12	17	24	31	38	45	53	60	67	75	82	90	97	105
114	106	99	91	84	76	69	61	54	47	39	32	25	18	12	10	12	18	24	31	39	46	53	61	68	76	83	91	98	106
113	105	98	90	83	75	68	60	53	45	38	31	23	17	11	9	10	18	25	32	40	47	54	62	69	77	84	92	99	107
111	104	96	89	81	74	66	59	51	44	37	29	22	15	9	[illegible]	12	19	26	33	40	48	55	63	70	78	85	93	100	108
110	103	95	88	80	73	65	58	50	43	35	28	21	14	8	7	13	19	27	34	41	49	56	64	71	79	86	94	102	109
109	102	94	87	79	72	64	57	49	42	34	27	19	12	7	7	13	20	27	35	42	50	57	65	72	80	87	95	103	110
108	100	93	85	78	70	63	55	48	40	33	25	18	11	6	7	14	21	28	36	43	51	58	66	73	81	89	96	104	111
107	99	92	84	77	69	62	54	47	39	32	24	17	10	5	[illegible]	15	22	29	37	44	52	59	67	75	82	90	97	105	112
•	98	91	83	76	68	61	53	46	38	31	23	16	9	5	X	16	23	31	38	46	53	61	68	76	83	91	98	106	113
105	97	89	82	74	67	59	52	44	37	29	22	15	8	5	10	17	24	32	39	47	54	62	69	77	84	92	99	107	115
103	96	88	81	73	66	58	51	43	36	28	21	14	7	6	11	18	25	33	40	48	55	63	70	78	85	93	101	108	116
102	95	87	80	72	65	57	50	42	35	27	20	13	7	7	12	19	27	34	42	49	57	64	72	78	87	94	102	109	117
101	94	86	79	71	64	56	49	41	34	27	19	13	7	8	14	21	28	35	43	50	58	65	73	80	88	95	103	110	118
100	93	85	78	70	63	55	48	40	33	26	19	12	[illegible]	9	15	22	29	37	44	51	59	66	74	81	89	97	104	112	119
99	92	84	77	69	62	54	47	39	32	25	18	12	9	11	17	23	31	38	45	53	60	68	75	83	90	98	105	113	120
98	91	83	76	68	61	53	46	39	31	24	18	12	10	12	18	25	32	39	47	54	61	69	76	84	91	99	106	114	122
97	90	82	75	67	60	52	45	38	31	24	17	12	11	14	20	26	33	41	48	55	63	70	78	85	93	100	108	115	123
96	89	81	74	66	59	52	44	37	30	23	17	13	12	16	21	28	35	42	49	57	64	71	79	86	94	101	109	116	124
95	88	80	73	65	58	51	44	36	29	23	17	13	13	17	23	28	36	43	51	58	65	73	80	88	95	103	110	118	125
94	87	79	72	65	57	50	43	36	29	23	17	14	15	19	24	31	38	45	52	59	67	74	81	89	96	104	111	119	126
93	86	78	71	64	56	49	42	35	29	23	18	15	16	20	26	32	39	46	53	61	68	75	83	90	98	105	113	120	128
92	85	78	70	63	56	49	42	35	28	23	18	16	18	22	27	34	41	48	55	62	69	77	84	91	99	106	114	121	129
91	84	77	69	62	55	48	41	34	28	23	19	17	19	23	29	35	42	49	56	63	71	78	85	93	100	108	115	123	130
90	83	76	69	61	54	47	40	34	28	23	19	19	21	25	31	37	44	51	58	65	72	79	87	94	102	109	116	124	131

○ Final location from SHIFT-H61

X Actual epicenter of Bourbon

--- Contour of actual standard deviation

Figure 9. Standard-deviation output from SIGRID; event Bourbon

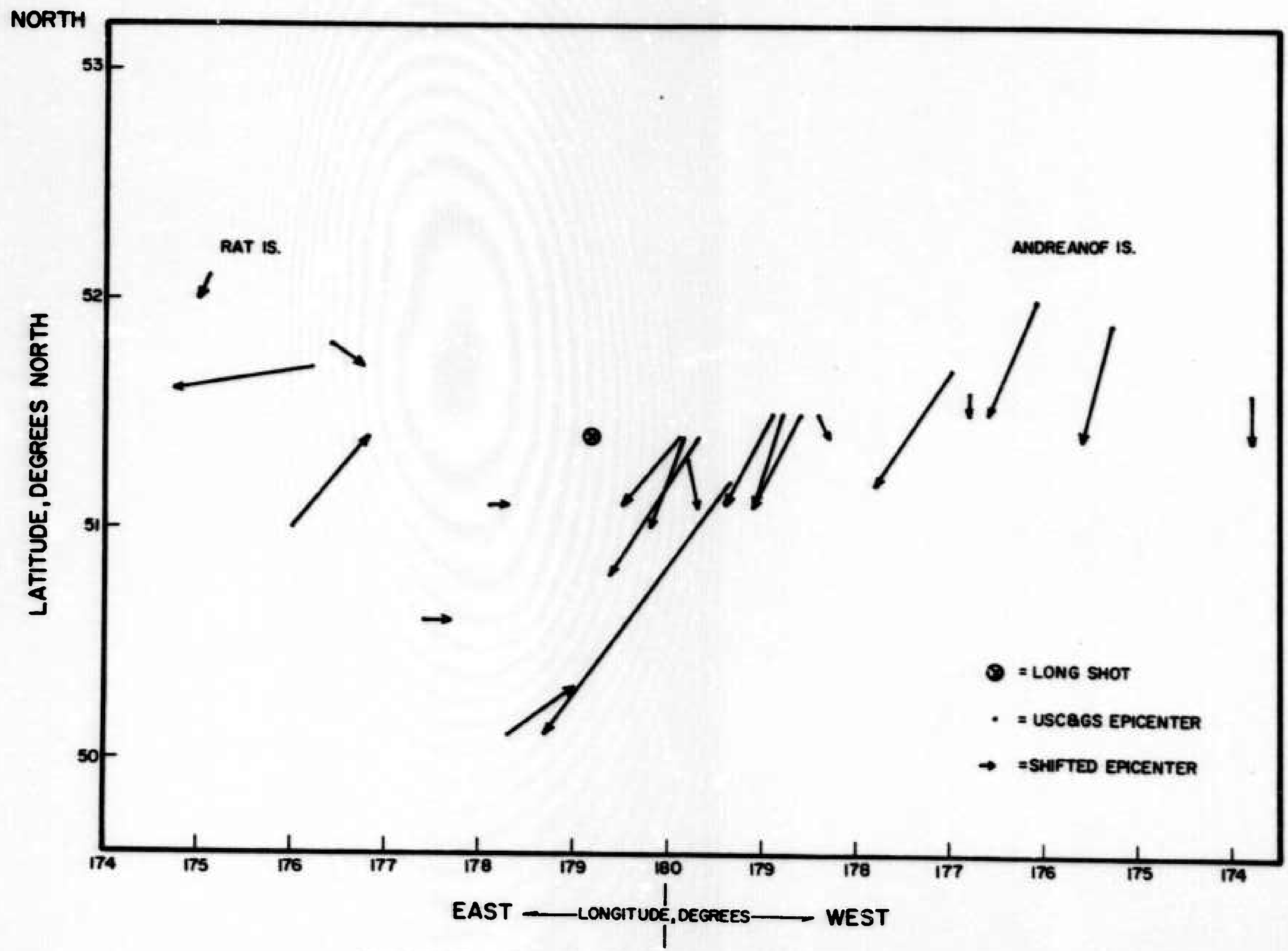


Figure 10. Location Shifts with LONGSHOT Anomalies

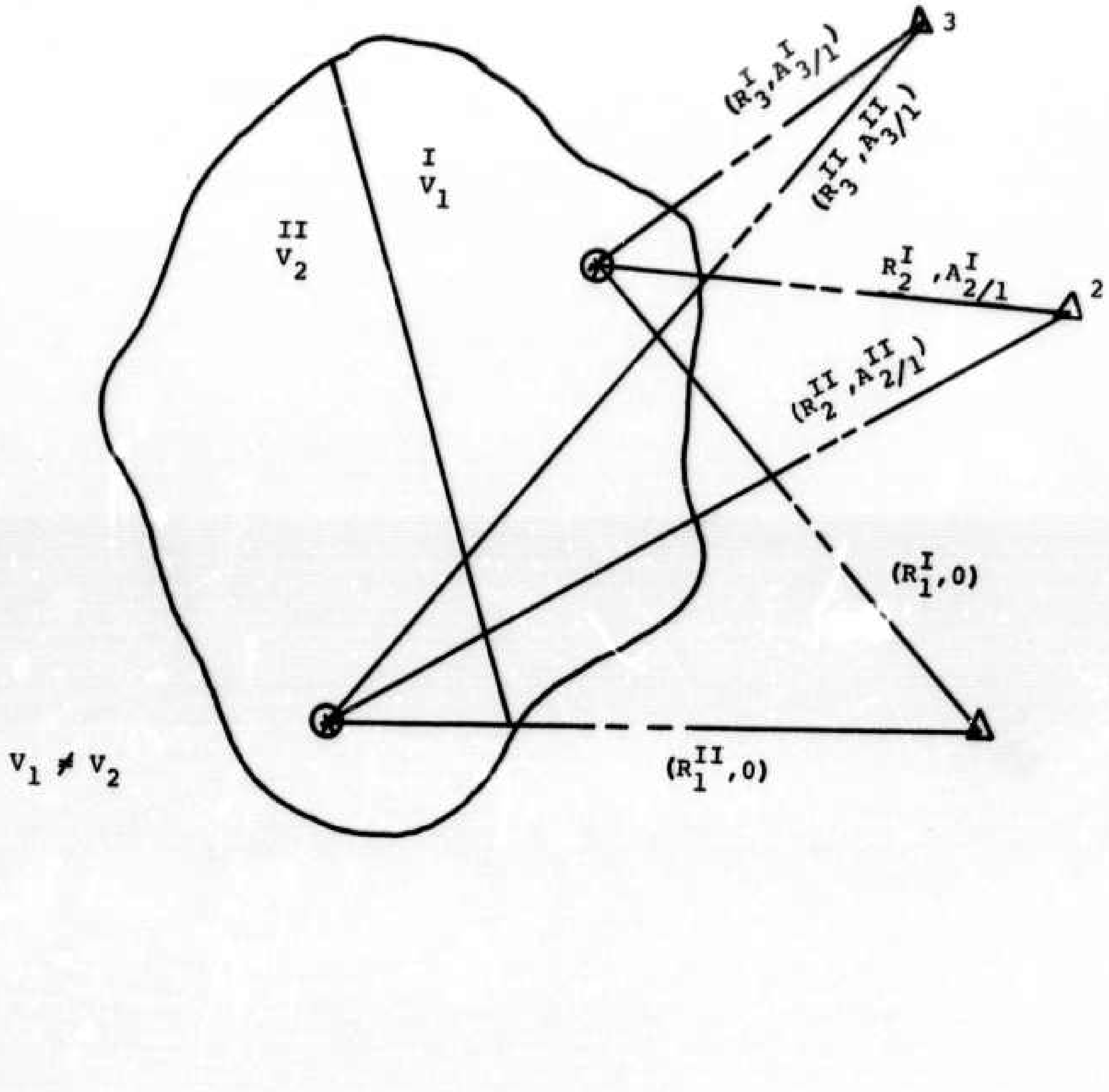


Figure 11. Faulted region illustrating difference when time-calibrating with residual R or anomolies A.

APPENDIX I

INPUT SEQUENCE FOR PROGRAM SHIFT

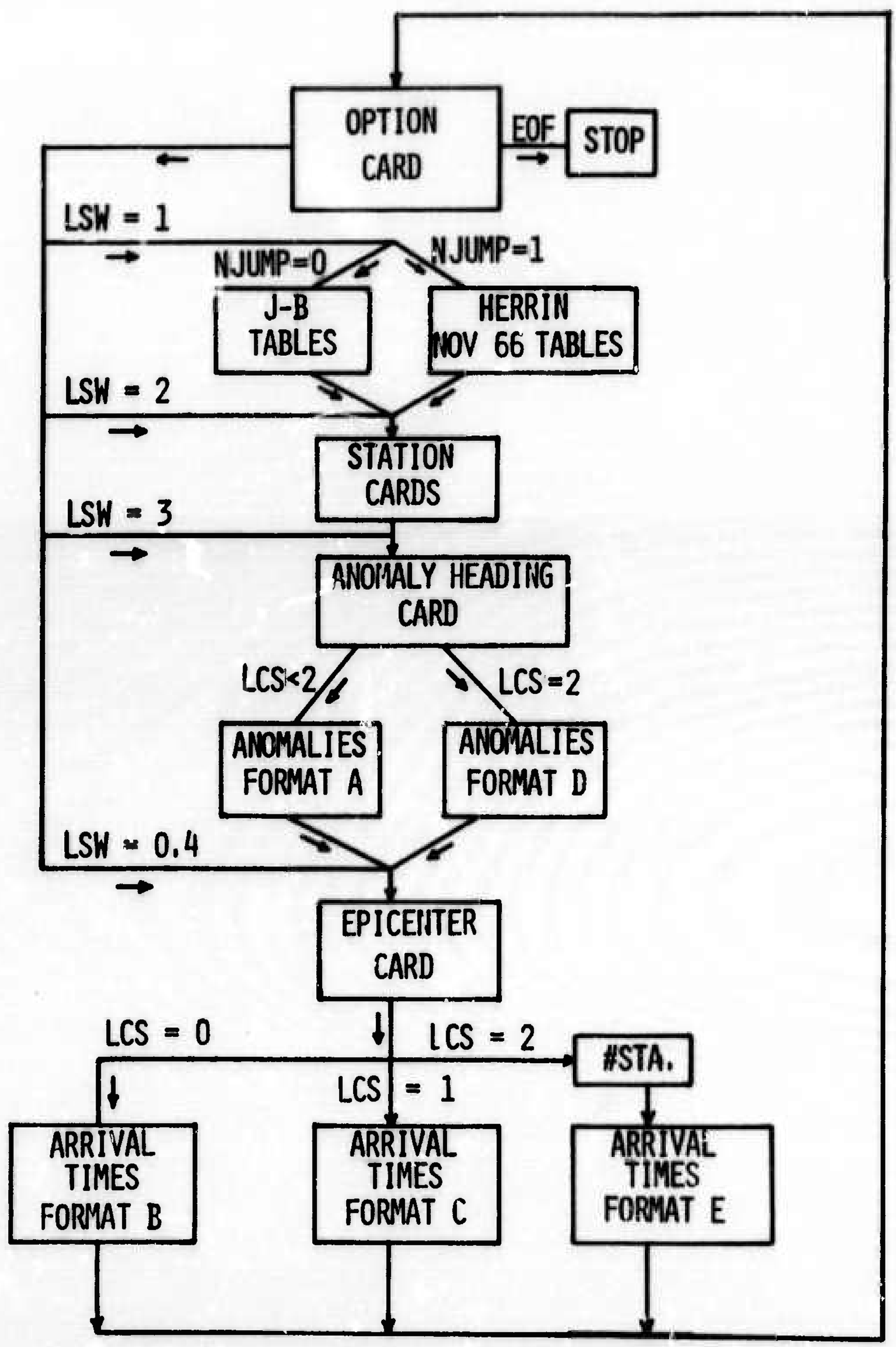


Figure A-1

INPUT CARD FORMATS AND PARAMETERS

OPTION CARD - FORMAT (7I2,4F5.0, 4I3)

NATS = Number of stations and anomalies in entire run of several cases. (Maximum of 50)

= 0: set to 21 internally

LSW = 1: Read input data beginning with travel-time table (See Figure A).

= 2: Read input data beginning with station deck.

= 3: Read input data beginning with anomaly-heading card.

= 0 or 4: Read input data beginning with epicenter card.

NJUMP = 0: Read J-B table (Tape 940, SDL)

= 1: Read Herrin 66 table (Tape 940, SDL).

LSC = 0: Read anomalies in Format A, arrival times in Format B.

= 1: Read anomalies in Format A, arrival times in Format C.

= 2: Read anomalies in Format D, arrival times in Format E.

IJK = 0: No SIGRID computation

≠ 0: Compute SIGRID

ISKIP = 0: Program locates epicenter

≠ 0: Program does not locate epicenter; computes SIGRID (if IJK ≠ 0) using input location coordinates.

NOUT = Flag requesting maximum-relative-error station subscripts in SIGRID

= 0: Do not print subscript matrix.

≠ 0: Print subscript matrix.

CT = Distance increment for computing time derivatives

= 0: Set to 0.01° arc internally.

SLOW = Factor to reduce the size of the iterative corrections to the event parameters

= 0: Set to 1 internally.

TEST = Incremental distance criterion for convergence

= 0: Set to 0.0001 internally.

CLAT = Grid increment, kilometers, for SIGRID computation

= 0: Set to 1.0 internally.

NCOL = Number of columns from SIGRID output grid

= 0: Set to 30 (maximum) internally.

KKEND = Number of lines from SIGRID output grid

= 0: Set to 30 (maximum of 100) internally.

ITER = Number of iterations allowed for location convergence

= 0: Set to 10 internally.

IMK = 0: Use input arrival times in SIGRID

≠ 0: Use predicted arrival times to grid center in SIGRID.

STATION CARDS - FORMAT (A5, 3X, 2(FS.0, F3.0, F5.1, A1), 24X, F5.0)

Column	Parameter
1-5	Station name
9-13	Station latitude, degrees
14-16	Station latitude, minutes
17-21	Station latitude, seconds
22	N or S
23-27	Station longitude, degrees
28-30	Station longitude, minutes
31-35	Station longitude, seconds
36	E or W
61-65	Station elevation, meters (not necessary)

ANOMALY-HEADING CARD - FORMAT (10A8)

Description of anomalies, region name, etc. May be blank card.

ANOMALY CARDS

Format A (8F10.4)

Format D (10X, F10.3)

Anomalies must be punched in same order as the station cards and equal to the number of stations. May be blank cards if unknown.

EPICENTER CARD - Format (2A8, A4, 2(F9.3, A1), F5.0)

Column	Parameter
1-20	Arbitrary name of event
21-29	Estimated latitude, decimal degrees
30	N or S
31-39	Estimated longitude, decimal degrees
40	E or W
41-45	Estimated depth, kilometers

ARRIVAL-TIME CARDS - (Zero input arrival time indicates no reading for that station)

FORMAT B (8(2F2.0,F6.3))

Column	Parameter
1-2	Arrival hour, station 1
3-4	Arrival minute, station 1
5-10	Arrival second, station 1
11-12	Arrival hour, station 2
13-14	Arrival minute, station 2
15-20	Arrival second, station 2
.	
.	
.	

Repeat, eight/card, until no. of times = no. of stations

FORMAT C (7F10.4)

Fields of 10, seven/card. Arrival time in seconds only.

FORMAT E (A5, 5X, 2F2.0, F6.3)

If this format is used, one card, Format (I5), indicating number of arrival times to be input, is required prior to time cards which follows:

Column	Parameter
1-5	Station name
11-12	Arrival time, hour
13-14	Arrival time, minute
15-20	Arrival time, second

With this format, one card/station with an arrival time is required.

APPENDIX II

Description of TIMEANOM Output.

The following description explains the presentation of the results in the computer output of the TIMEANOM with these reference numbers appearing in Table VIII.

1. Source of expected travel times. For Table VIII, the Herrin table, November 1966 version, is used; for Table IX, the JB table; for Table X, the Herrin 61 table.

2. Reference station, R, selected for computing relative anomalies. In this report, all anomalies are relative to station RK-ON. The following relation may be used to change reference stations;

$$A_{i/j} = A_{i/r} - A_{j/r}$$

where $A_{i/j}$ is the anomaly at station i relative to a new reference station j.

3. All expected travel-times in this report have been corrected for the ellipticity of the earth such that the computed anomalies may be used in conjunction with other programs requiring these corrections.

4. An arbitrary geographic name given to the event region.

5. Range of epicentral distance in the event region.

6. Range of epicentral azimuth in the event region.

7. Date and arbitrary name given to each event.

8. Epicentral distance, in kilometers, from the reference station, R.

9. Epicentral azimuth, in degrees measured from north to east, from the reference station, R.

10. Station designator, i.

11. Measured travel-time anomaly in seconds, at station i relative to station R for the kth event;

$$A^k_{i/r} = T^k_i - T^k_r - H^k_i + H^k_r$$

where T is the observed arrival time and H is the expected (Herrin 1966) travel time from the hypocenter of the kth event including correction for ellipticities but <u>not</u> for station elevations.

12. A fixed-point zero anomaly indicates that no reading was made at the station for that event.

13. The average anomaly at station i of N recorded events;

$$\bar{A}_{i/r} = \left(\sum_{k=1}^{N} A^k_{i/r} \right) /N$$

for the defined region.

14. Standard deviation, or error of estimate, at the ith station for N observations:

$$\sigma_i = \left\{ \left[\sum_{k=1}^{N} (A^k_{i/r} - \bar{A}_{i/r})^2 \right] /(N-1) \right\}^{1/2}$$

for the defined region.

15. Number of observations, N, at station i for the defined region.

16. Total number of epicenters included in the defined region.

17. Epicenter latitude, degrees (USC&GS); plus north, minus south.

18. Epicenter longitude, degrees (USC&GS); plus east; minus west.

19. Event depth, kilometers (USC&GS).

20. Event origin time, hours, minutes, seconds (USC&GS).

21. Standard deviation, or error of estimate, of the kth

event in the defined region;

$$\sigma_k = \left\{ \left[\sum_{i=1}^{L} (A^k_{i/r} - \bar{A}_{i/r})^2 \right] / (L-1) \right\}^{1/2}$$

where L is the number of stations recording the kth event not including the reference station R.

22. Average error, or bias, of the kth event;

$$E_k = \sum_{i=1}^{L} (A^k_{i/r} - \bar{A}_{i/r})/L$$

where L is the number of stations recording the kth event not including the reference station R.

23. Standard deviation of the kth event in the defined region, with the reference-station bias E_k removed:

$$\sigma'_k = \left\{ \left[\sum_{i=1}^{L} (A^k_{i/r} - E_k - \bar{A}_{i/r})^2 \right] / (L-1) \right\}^{1/2}$$

24. Number of stations, L, recording the kth event, not including the reference station R.

The program TIMEANOM permits a rapid determination of travel-time anomalies for a network and for a set of events within a region, and it can be used to isolate spurious readings or blunders at the stations or, for earthquakes, possible mislocations.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)
TELEDYNE, INC.
ALEXANDRIA, VIRGINIA

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3 REPORT TITLE
PRECISION LOCATION OF UNDERGROUND NUCLEAR EXPLOSIONS USING TELESEISMIC NETWORKS AND PREDETERMINED TRAVEL-TIME ANOMALIES

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific

5 AUTHOR(S) (Last name, first name, initial)
Chiburis, E.F.

6. REPORT DATE
1 March 1968

7a. TOTAL NO. OF PAGES
50

7b. NO. OF REFS
5

8a. CONTRACT OR GRANT NO.
F 33657-67-C-1313

b. PROJECT NO.
VELA T/6702

c. ARPA Order No. 624

d. ARPA Program Code No. 5810

9a. ORIGINATOR'S REPORT NUMBER(S)
214

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10 AVAILABILITY/LIMITATION NOTICES
This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Chief, AFTAC.

11 SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
ADVANCED RESEARCH PROJECTS AGENCY
NUCLEAR TEST DETECTION OFFICE
WASHINGTON, D. C.

13 ABSTRACT

Using a series of 19 explosions detonated within a 2500 km^2 area of the Nevada Test Site, the effectiveness is demonstrated of applying predetermined travel-time anomalies to a limited network of teleseismic stations (comprised of between 4 and 13 stations greater than 1900 km distance). Three different travel-time tables were used: Jeffrey-Bullen; Herrin, 1961 version; and Herrin, November 1966 version; and two different computer programs: LOCATE and SHIFT, the former which minimizes the sum of squares of residuals and the latter which minimizes the sum of squares of relative residuals. The mean location error obtained without time anomalies is about 26 km, and with anomalies is less than 3 km, regardless of travel-time table and regardless of program.

It is further demonstrated that neither the number of stations nor the distance aperture of the network has an effect on the location error, although the azimuth aperture does.

Confidence estimates are made in three ways: the standard confidence ellipses; maximum-relative-error polygons; and standard-deviation contours about the final solution. It is shown that by applying travel-time anomalies, the standard confidence ellipses can be reduced in area by factors of 1/5 to 1/152 and still contain the true epicenter.

A discussion is given of the stability of travel-time anomalies across the Nevada Test Site area, and of some problems involved in determining usable anomalies from earthquakes.

14 KEY WORDS

Unclassified
Security Classification